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USING OPTIMIZATION TO IMPROVE NASA EXTRAVEHICULAR ACTIVITY PLANNING

by

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September 2012

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Extravehicular Activity (EVA) is a specialized function performed during spaceflights in which two or more astronauts don spacesuits to perform tasks on the exterior of their spacecraft. An extensive and iterative planning process is required to prepare for each highly choreographed EVA operation. The current planning process relies heavily upon time-consuming heuristic approaches by subject matter experts to essentially "hand-build" each EVA plan. This research develops the EVA Planning Model (EPM), a linear, mixed-integer program intended as a proof-of-concept demonstration for employing formal mathematical optimization techniques to EVA planning. The EPM is thoroughly tested to verify that it functions as intended and is evaluated by expert EVA planners using actual task information. We find that the EPM proves the concept that formal mathematical optimization can be used to aid in subject matter experts in EVA development and planning. It is particularly useful in allowing the evaluation of alternative planning inputs and thorough assessment of EVA plan impacts resulting from external changes.

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USING OPTIMIZATION TO IMPROVE NASA EXTRAVEHICULAR ACTIVITY PLANNING

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Extravehicular Activity (EVA) is a specialized function performed during spaceflights in which two or more astronauts don spacesuits to perform tasks on the exterior of their spacecraft. An extensive and iterative planning process is required to prepare for each highly choreographed EVA operation. The current planning process relies heavily upon time-consuming heuristic approaches by subject matter experts to essentially "hand-build" each EVA plan. This research develops the EVA Planning Model (EPM), a linear, mixed-integer program intended as a proof-of-concept demonstration for employing formal mathematical optimization techniques to EVA planning. The EPM is thoroughly tested to verify that it functions as intended and is evaluated by expert EVA planners using actual task information. We find that the EPM proves the concept that formal mathematical optimization can be used to aid in subject matter experts in EVA development and planning. It is particularly useful in allowing the evaluation of alternative planning inputs and thorough assessment of EVA plan impacts resulting from external changes.

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LIST OF ACRONYMS AND ABBREVIATIONS

ATSP	Asynchronous Travelling Salesman Problem
CPU	Central Processing Unit
CR	Critical Ratio
EDD	Earliest Due Date
EMU	Extra-vehicular Mobility Unit
EPM	EVA Planning Model
EV1	Extra-vehicular Crew Member #1
EV2	Extra-vehicular Crew Member #2
EVA	Extra-vehicular Activity
GAMS	General Algebraic Modeling System
HPF	Highest Priority First
ISS	International Space Station
LEE	Latching End Effector
MIP	Mixed Integer Program
MOD	Mission Operations Directorate
NASA	National Aeronautics and Space Administration
NBL	Neutral Buoyancy Laboratory
ORU	Orbital Replacement Unit
PET	Phase Elapsed Time
PR	Priority Ratio
R&R	Removal & Replacement
SSRMS	Space Station Remote Manipulator System
TSP	Travelling Salesman Problem

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EXECUTIVE SUMMARY

Extravehicular Activity (EVA) is a specialized function performed during spaceflights in which two or more astronauts don spacesuits to perform tasks on the exterior of their spacecraft. Performing an EVA involves substantial preparatory costs in terms of severely limited resources and astronaut crew time. EVA operations also place the participants in extreme danger from a multitude of sources. As a result, EVA plans must be highly choreographed to achieve the maximum value from each operation. Since the advent of EVA capability in the mid-1960s, NASA has used teams of extensively trained and experienced subject matter experts from the Mission Operations Directorate to carefully plan these activities. They undertake an elaborate and iterative process to transform raw requirements from the program customer (currently, the International Space Station) into a highly efficient, executable EVA timeline.

Given the evolutionary development process and repeated re-working of the plan required throughout the planning phase, tools that can assist the planning experts may result in significant savings or enhanced plan quality. We develop the EVA Planning Model (EPM), a linear, mixed-integer program intended as a proof-of-concept demonstration for employing formal mathematical optimization to EVA planning.

The nature of EVA planning presents us with a difficult challenge in terms of proving model functionality and quality. We address this partly by introducing a methodical and thorough testing regimen derived from the field of software engineering and adapted to our mathematical model. The proof-of-concept culminates with the use of EPM to build EVA plans using actual planning data from subject matter experts. Expert opinion surveys are then conducted to obtain an evaluation of the concept and execution of the EPM, its usefulness, strengths, and weaknesses.

Our assessment of EPM and the survey's results suggest that EPM establishes the basis for (and warrants further research on) a formal mathematical optimization that can be used to aid subject matter experts in EVA development and planning. EPM creates credible EVA timelines that match or exceed the effectiveness of human built solutions,

and allows for trade-off evaluation and "what-if" scenario analysis that can be valuable to the planning community in a variety of ways.

The EPM, as developed in this research, has some significant limitations. Among them are (1) a primitive user interface, (2) a lack of functionality in several important areas (i.e., robotic arm integration and tool constraints), and (3) highly variable model performance in terms of solution times. We recommend future improvements that can be made to address these weaknesses and increase the model's capabilities and usefulness.

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Many people contributed to this work both directly and indirectly. I am especially grateful to those mentioned here for their aid and support.

First, my wife Kathryn who has been my guiding light and driving force since long before this thesis was begun. During my time as a student at the Naval Postgraduate School, she has shouldered the burden of virtually all familial duties in our household while working full-time herself. She's the best wife and mother a family could hope to have. My daughter, Alexandra, provided motivation and perspective throughout my studies. Her conviction that reading a bedtime story with her dad was at least as important as him finishing just one more paragraph was a needed reality check.

I could not have found a better thesis advisor than Dr. Javier Salmeron. He is a wizard with mathematical formulation (and troubleshooting) and his devotion to this project equaled my own. He responded immediately to my pleas for assistance countless times and saved many hours of frustration with his clear and concise guidance. A fellow student from NASA, Mr. Dan Mulligan, was a critical partner in defining the initial formulation of the optimization model that has been fully developed in this work. Aside from that contribution, his exceptional abilities and willingness to help others provided inspiration throughout my time at NPS.

I am also indebted to Mr. Faruq Sabur of the EVA Group at NASA Johnson Space Center. He was my point of contact and educator for all things EVA planning and went out of his way to help me learn the nuances of the planning job. Additionally, I was the beneficiary of Ms. Dana Weigel's knowledge and experience as an EVA Officer and Flight Director. Ms. Jaclyn Kagey and Ms. Allissa Battocletti took time out of their busy schedules to help me use their EVA as a test case for the model developed in this thesis.

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I. INTRODUCTION

Extravehicular Activity (EVA) is a specialized function performed during spaceflights in which two or more astronauts don spacesuits with self-contained life support systems (extravehicular mobility units or EMUs) to perform tasks outside of the spacecraft. These tasks range in purpose from the deployment or retrieval of scientific experiments to vehicle maintenance or assembly. The standard EVA is a 6.5-hour-long operation (limited by EMU consumables and crew endurance) in which two crew members perform a series of tasks as outlined in a detailed plan.

Since Ed White performed the first U.S. spacewalk in June 1965 (Portree & Trevino, 1997), the National Aeronautics and Space Administration (NASA) has made tremendous advances in techniques, support equipment, and operations related to EVA. The construction and maintenance of the International Space Station (ISS) has relied heavily upon the use of EVA. To date, 127 U.S. EVAs have been conducted in support of the ISS assembly and its on-going mission. The design of the vehicle is such that EVA operations will continue to be a frequent and critical part of its upkeep for the life of the program, projected to extend to between the years 2020 and 2028. (NASA, 2010a).

Though NASA has leveraged its 47 year history with EVA to build a record of overwhelming success throughout the ISS program, there are still areas with potential for improvement. In particular, the planning of EVAs remains a very labor-intensive process which relies heavily on individual expertise and multiple iterations between different stakeholders. In effect, each EVA is hand-built by a team including the Mission Operations Directorate (MOD) flight controllers, the astronaut crew, and the EVA Project Office.

A. HIGH LEVEL PLANNING PROCESS

The normal process of planning an EVA takes several months and generally includes the considerations discussed in the following subsections.

1. Overview of the Planning Process

There are several phases in the planning process from conception to execution. Depending on the program, mission, and situation, the need for an EVA can generally be categorized into three groups: those driven by a single high priority task, those composed of a collection of tasks built up on a "to do" list, and those necessitated by a vehicle system failure or other contingency situation.

Once a need is identified, the customer program generates requirements (in the form of tasks), prioritizes them, and organizes them into their best estimate of EVA-sized groups. These requirements are evaluated by the MOD planners who create draft overview timelines for an individual, or series of EVAs. This process is an iterative, back-and-forth exchange in which the planning experts generate a first heuristic timeline. Any proposed alterations to the initial allocation or prioritization of tasks which may have an impact on the plan must be negotiated between MOD and the customer program office.

Once a basic mapping of tasks to a given EVA is completed, the planners will subdivide and order tasks to maximize efficiency of the plan. Many considerations are taken into account in this process: the locations of tasks, required support equipment, availability and location of spare parts and tools, translation times and paths from one task to another, astronaut body positioning, lighting conditions, hazard controls, etc. These considerations result in a draft of a detailed plan which has a high level representation called a summary timeline. When this is developed, the astronaut crew is introduced to the plan and training begins.

Although the activity is called training, it is equal parts practice for the crew and further development and refinement of the plan. Several facilities are utilized in this phase of development, starting with basic desktop review and proceeding to the more elaborate Virtual Reality Lab to practice fine, close-up work and spacial relations. Simultaneously, training is conducted in the Neutral Buoyancy Lab (NBL) for full dress rehearsal. The active response gravity offload system is a facility that helps the crew

practice body control and manipulating masses in zero-gravity. Other training aids, such as an air bearing floor and camera and photo labs are used to help the crew practice more detailed facets of EVA.

Throughout the training phase, the EVA timeline is constantly refined as data is gathered on the duration of tasks and potential issues are noted. In some cases, a better understanding of the time duration of tasks and their interactions could lead to the removal or addition of tasks to the plan. The planners are constantly gathering data from the training exercises and the other coordination processes that are concurrent. There is a continuous flow of detailed requirements related to interfaces, hardware, and special constraints. The plan is filled out and iterated throughout this period.

The above description is a simplified look at the high level steps in the planning process, but it is important to realize there is much more complication in the planning process than can be presented here. Many layers of detail underpin the creation of an executable EVA plan. A simple example of the increasing levels of detail considered as the plan matures is what the planners call "bag-ology." This is the pseudo-science of planning the contents, packing, use, transportation, deployment, and management of the storage bags the crew will use during the EVA. Understanding what equipment, tools, and spare parts must be placed in bags, how and when they will be used, and how and where they can be temporarily stowed is an exhaustive process. It alone can take many hours of research, development, training runs, and iterations to finalize. Similarly detailed work is required to incorporate hazard analysis, orbital replacement unit (ORU) mass, center of gravity, and moment of inertia data, equipment jettison protocols, tool settings, tether "tie downs" to restrain lose equipment, predicted solar radiation conditions, etc.

The final phase of the process is execution. This phase is the most time-compressed and dynamic. Crew performance can exceed expectations, creating free space to accommodate more tasks, or problems could arise, forcing a restructuring of the remainder of the in-progress EVA or of subsequent EVAs. In-progress re-planning is the most time-critical aspect of the process and has the potential for the most gain, but also the most risk in terms of opportunity cost.

Figure 1 shows the basic flow of the planning process. This thesis is concerned mainly with high-level planning, thus many of the intermediate process details are omitted from the flow chart.

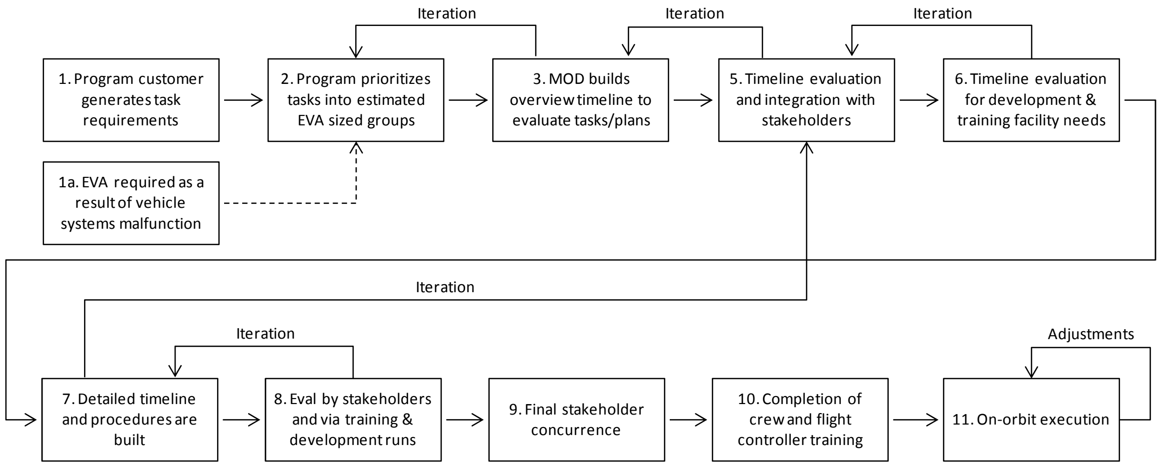


Figure 1. Simplified EVA Planning Process Diagram

2. Planning Considerations

Cost is a primary consideration in planning an EVA. A start-up cost results partly from the need to physiologically condition the crew for the low pressure, 100%-oxygen environment of the EMU suit. Four different pre-conditioning protocols (called pre-breathe) have been approved and employed, but all of them use oxygen and nitrogen stored in high-pressure tanks aboard the ISS and a significant amount of crew time (Brown & Jarvis, 2011). Although the ISS has systems to recover much of the atmospheric gas that would otherwise be vented overboard during depressurization of the airlock, the air that is not recovered is a factor in the cost as well. Gaseous resources like oxygen, nitrogen, and air must be fastidiously conserved aboard a long duration vehicle such as the ISS and will be even more critical on any future deep-space platform. Approximately 12 kilograms of oxygen is expended from the ISS high-pressure gas tanks for each EVA. Crew time is also an important resource aboard the ISS, where every minute spent on systems maintenance or tasks like EVA preparation takes away from time devoted to scientific experiments. The investment for pre-breathe, which is in addition to the time required for tool, equipment, and self-preparation, can range from four hours for the "in-suit" pre-breathe to an overnight "campout" protocol that stretches

over two crew days. The time cost is also very significant on the days and weeks prior to the EVA. Suit checkout, maintenance, and fit verifications, tool preparation, battery charging, water filtering, and planning conferences with mission control add significant time as well.

It must be considered that all gaseous consumables used for EVA preparation must be brought to Earth orbit. As a result of high launch costs, estimated by the U.S. House of Representatives Subcommittee on Space and Aeronautics at approximately $20,000 per pound (NASA's Commercial Cargo Providers, 2011), these resources, along with crew time, must be spent very wisely.

Another factor in EVA planning is the relatively high risk of these operations. The spacewalking crew is working in the most hazardous and hostile conditions. Some of the risks are environmental, such as the vacuum of space, extreme temperatures, radiation, and micrometeoroid and orbital debris impacts. Other risks are occupational, related to the work and equipment: suit snags and leaks, entanglement, hazardous materials, loss of positive contact with the vehicle or tethers, handling massive objects, and EMU suit systems malfunctions. All of these risk factors can lead to serious injury or death for the crew.

These costs and risks drive some basic guidelines for planning. First, all EVA operations are planned to utilize the maximum duration of EVA time and minimize the total number of EVAs to accomplish the required tasks. Second, all time outside the vehicle is considered precious and every minute must be planned to maximum effect. Third, all EVAs must have at least two crew members to allow for a "buddy system" in case of emergency. Additional planning considerations are employed to address these and other costs and risks, many of which will be discussed in detail in the planning model formulation presented in Chapter II.

3. Special EVA Planning Driver: Big 12 Failures

One special case of requirements generation shown in Figure 1 deserves special attention. Block 1a shows that EVA requirements can be driven by vehicle systems malfunctions. With the ISS at the "assembly complete" phase, one of the biggest drivers

for EVA is the potential for systems failures which require removal and replacement of ORUs on the exterior of the vehicle. The ISS program has identified 12 contingency EVAs which would require relatively immediate implementation. Each EVA corresponds to the resolution of a specific ORU or functional failure aboard the ISS and this list of EVAs (and/or their triggering failures) has been dubbed the "Big 12" by the ISS operations team and program. Criteria to be included in the Big 12 is formally described by the ISS program as "the failure of the function provided by the ORU causes a situation placing the ISS in a configuration that is zero fault tolerant, or effectively zero fault tolerant, to survival" (NASA & Roscosmos, 2011). The ability to handle the Big 12 failures via EVA repairs is such an important concern that it is currently one of the top four program risks identified by the ISS Program Risk Advisory Board (Uhran, 2012).

Since the failure modes are known, these EVAs can be planned to a basic level ahead of time, but the uncertainty of when they might occur drives many planning complications. The unknowns are many: the crew members who will perform the EVA, the condition of the vehicle, the status of supporting equipment and systems (such as robotics), any secondary schedule drivers (such as the impending arrival of a resupply vehicle), any other outstanding tasks that could be added to a Big 12 EVA, etc. The uncertainty puts tremendous pressure on the planning process, which must be accelerated significantly to address the urgency of the situation. On July 31, 2010 an external thermal control pump module failed aboard the ISS (a Big 12 failure), driving the need for three contingency EVAs to replace it. The first of these EVAs was executed just six days after the malfunction, the second and third followed in the following nine days (NASA, 2010b). Clearly, such an intensive sequence of operations stresses the planning process in the extreme.

B. SUMMARY TIMELINE DEVELOPMENT

One of the first steps in the planning process is to arrange tasks into groups that conceptually represent EVAs. As noted in Figure 1, the program customer begins the process by identifying tasks and assigning relative priorities to them. The program then estimates the task durations and produces a conceptual EVA which is simply a collection of tasks they expect will fit into one or more EVAs. MOD takes this input and applies the

first of many evaluations to its feasibility and efficiency by creating a summary timeline (sometimes called an overview timeline). The effort required to produce a summary timeline requires approximately one week for one to two experts. It is the basis of iteration in the planning process and may be repeated, in part or as a whole, several times. This iteration is essentially an education and negotiation process for the program customer whereby task priorities and groupings can be debated on the basis of the efficiency of the resulting EVA. This process continues as the planners work through the steps in Figure 1. Often, new information or changes late in the process can lead to renegotiation with the program customer, resetting the process back to a very early stage. Thus, many summary timelines may be built throughout the development of a single EVA.

Figure 2 shows three examples of summary timelines for EVAs that have either been completed or are in the planning stage. The format shown is one of several used regularly in EVA planning and will be used throughout this research. Two rows in each graphic represent the task assignments for each of the crew members, always designated EV1 and EV2, respectively. Phase elapsed time (PET), a measure of time that begins when the crew exits the spacecraft, increases to the right. The top timeline is for a nominal EVA, meaning it contains tasks which are driven by planned program requirements rather than a need to address equipment failures. The second timeline is for a similar nominal EVA, but one which does not have enough tasks to fill a full, 6.5-hour EVA. This can happen if there are not enough tasks in the queue when an EVA is scheduled or because the planners are especially concerned that some tasks could take longer than planned. As a result, time is left in the plan for so-called "get-ahead" tasks. This allows the EVA flight controllers to slot additional tasks into the extra time in near real-time as long as the scheduled tasks do not run over time. The third timeline is for a contingency EVA, one that would only be performed as a response to a system failure or other unplanned event. As can be typical for this type of EVA, the planned tasks do not run the full allowable duration, leaving open the possibility of adding other tasks to the timeline in near real-time.

The remainder of this section elaborates on details that must be considered whenever a summary timeline is generated.

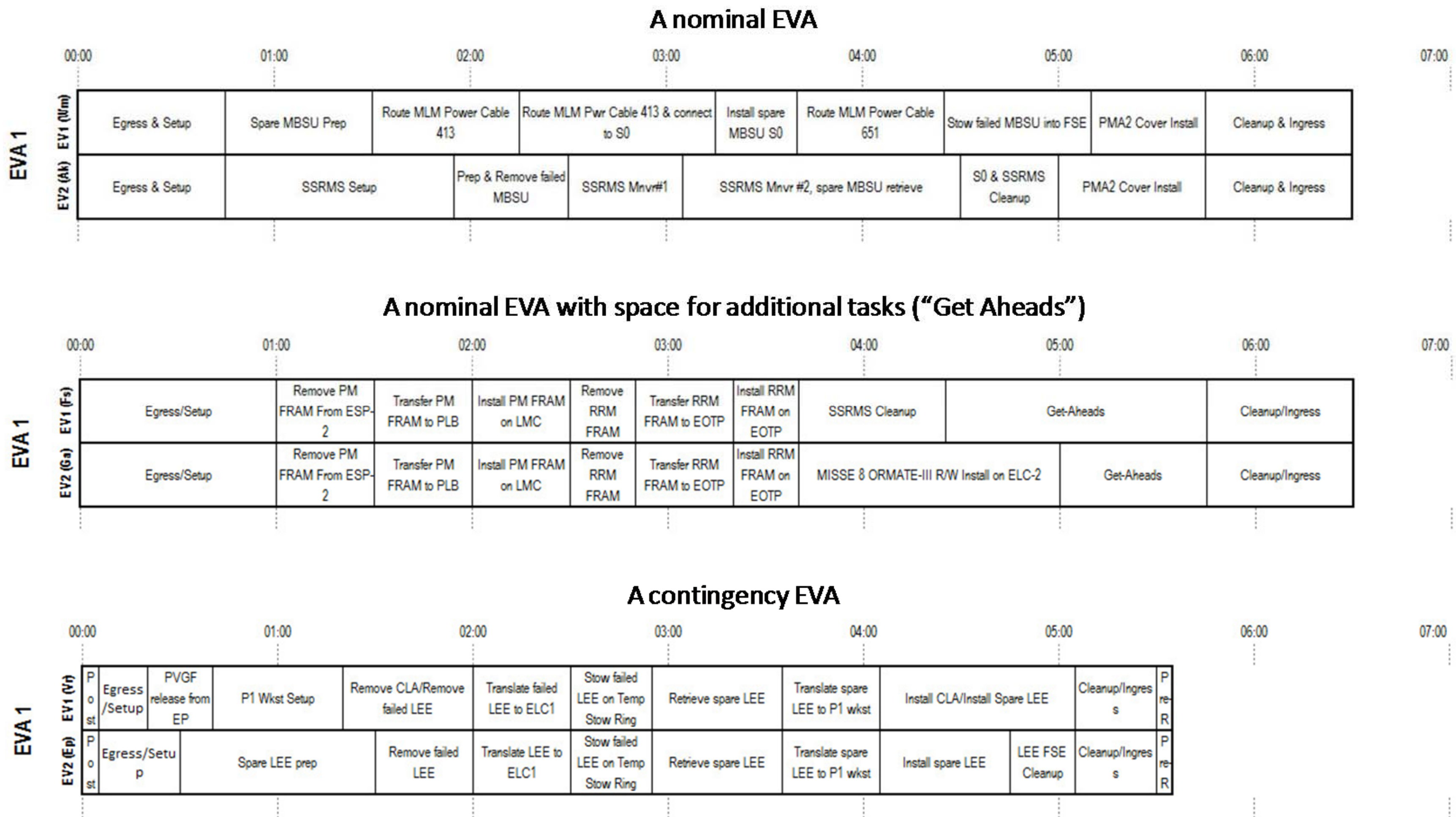


Figure 2. Examples of Summary Timelines

1. Task Priority

Generally, tasks will be ordered in an EVA timeline with deference to their priority. Scheduling the highest priority tasks first gives the highest probability of completion of those tasks in the event the EVA must be terminated early due to suit malfunctions or other problems.

There are cases, however, where performing a lower priority task first creates a valuable time efficiency or reduces idle time. As such, the schedule cannot be driven by priority alone. The process of summary timeline creation can identify situations like this which usually provide useful data to inform a renegotiation with the program customer to ensure they understand the benefits and shortcomings of scheduling tasks strictly in priority order.

2. Task Duration

Each task is assigned an estimated duration when it is first proposed. Refining this duration is one of the goals of the training and development process. This refinement has parallels to cost estimation in a normal program development process. In some cases, the task (or a similar task) will have been performed previously, allowing the planner to consult a database of actual duration information for a specific task. As each task is practiced in the high fidelity simulators, the understanding of its duration is improved further. Up to three NBL runs are dedicated to task and timeline duration validation in normal circumstances, with the possibility of more if the tasks and procedures are immature or untried (Brown & Jarvis, 2011).

Once enough data are available to make good estimates of task durations, several modifying factors are considered. A skill rating is assigned to each crew member based on their background, experience, and aptitude level. This rating is used to adjust the time required for tasks, especially in cases where the crew performing the EVA are not the same astronauts who participated in the ground training. Another modifier is a multiplication factor applied to task durations derived from 1-g training. Experience has shown that tasks simply take longer when performed in the microgravity environment of

space and working with actual flight hardware. Depending on the task, this multiplier could double the expected time to complete the same task on-orbit as compared to 1-g training.

3. Task Location

The ISS is a vast structure in space vehicle terms. It is roughly the shape of a cross, with a 109-meter truss extending along one axis and a 51-meter axis containing the pressurized modules (NASA, 2011). Practically any location on the exterior of the ISS could be an EVA worksite, but typically worksites will be centered at the locations of installed equipment (i.e., ORUs). To give a general understanding of the magnitude of the number of possible worksites, Figure 3 shows the locations of all ORUs installed on the truss segment. Each red circle and pointer represent one installed ORU on the truss. There are many more worksites on the exteriors of the pressurized modules which are not shown in this diagram.

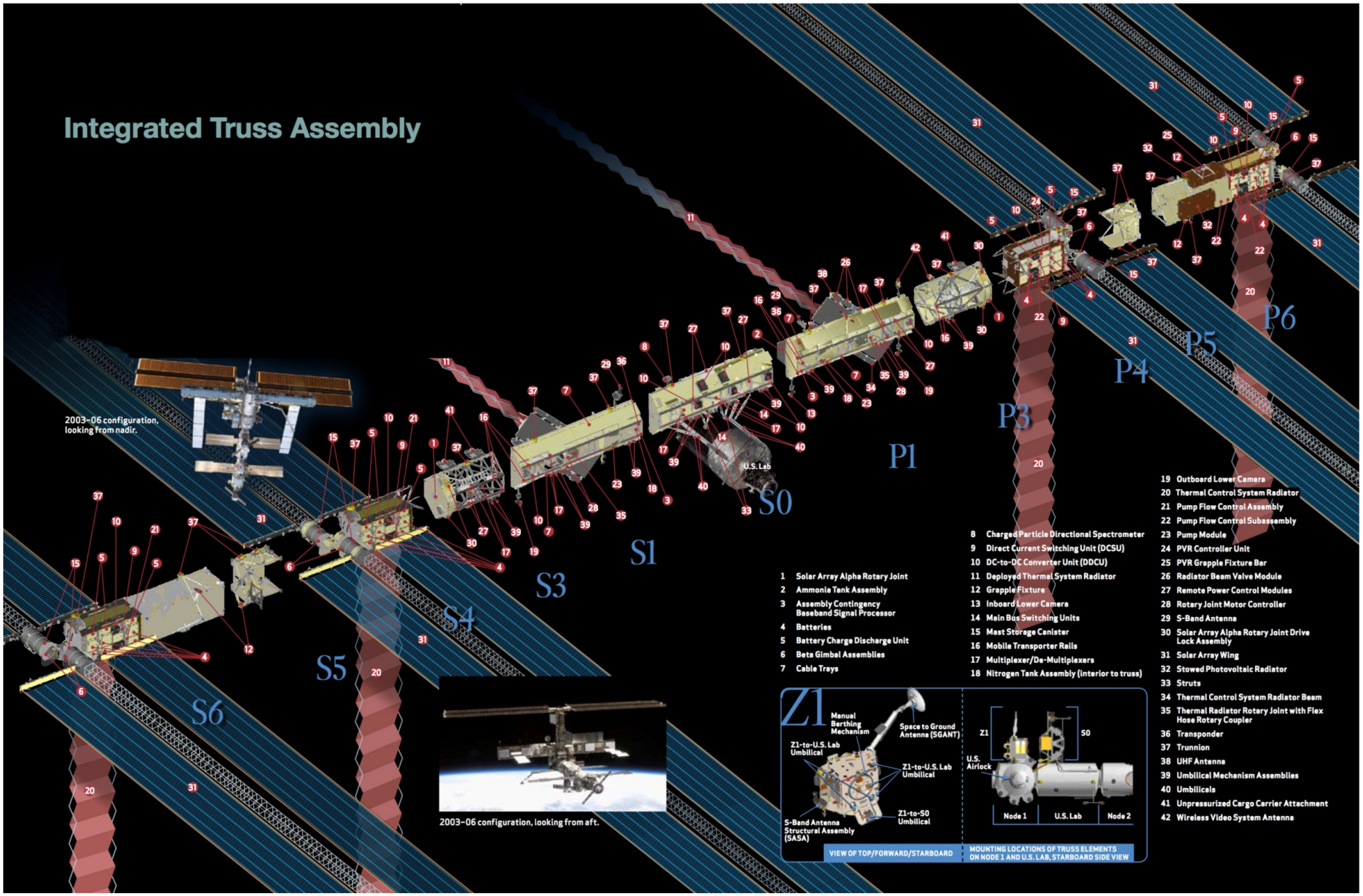


Figure 3. Truss ORU Map (from NASA, 2010c)

Task location is important because the crew must move from worksite to worksite in order to perform their jobs. This movement is typically a manual "crawling" from place to place but can also be aided by the robotic arm. Navigating across possibly sensitive equipment, avoiding snag hazards, managing body position, observing proper tether protocol, and ingress or egress of portable foot and body restraints contribute to the time required to move from one location to another.

4. Task Precedence

Tasks must be ordered properly to comply with any prerequisites that must be completed before a given task may be undertaken. Precedence relationships between tasks can be the result of a physical need, or be stipulated by the planners in order to gain efficiencies. An example of the former is disconnecting electrical connectors before a piece of equipment can be removed. In the latter type, planners may consider operational reasons, such as waiting to retrieve a replacement part until the old one is successfully removed. Otherwise, if unforeseen problems prevent the removal of the old part, any time spent retrieving the new one will have been wasted.

5. Task Synergy

Some tasks may be much easier or quicker to perform if they are scheduled either in conjunction with or following other specific tasks. For example, consider a task which has no mandatory predecessors, but would take 50% less time if performed following another task. Benefitting from this type of efficiency works hand-in-hand with non-binding task precedence as described in the previous sub-section.

6. Special Task Timing Requirements

Some tasks have special timing requirements which must be taken into account in planning. Some examples are:

a. Day/Night Constraints

The orbital speed of the ISS leads to a unique work environment in which the sun rises and sets every 90 minutes. This results in four day and four night periods

during the typical 6.5-hour EVA and has an effect on both the lighting and thermal conditions that can impact task timing. Some tasks can only be performed in daylight or only in shadow, and some others must be timed such that they do not cross a day-night boundary. Fluid connector mate or de-mate is an example of a task that should not be performed across a day-night boundary because the large temperature swings can cause "hydraulic lockup" of the connector as pressure changes inside the fluid lines.

b. Thermal Clocks

Thermal constraints are of considerable concern. Most electrically powered exterior ORUs have rigid temperature constraints that are met only when the equipment is powered or supported by heaters. EVA crews routinely have to remove power from, and relocate these devices. As soon as power is removed, a so-called "thermal clock" begins ticking down to the ORU's lower temperature limit. The time window allowed before power must be re-applied is provided by engineering analysis prior to the EVA.

c. Support Systems Interaction

Many tasks require support from other systems on the vehicle. Typical interactions include: de-energizing an electrical bus before the EVA crew disconnects a wire, stopping the rotation of the moving equipment near the crew's work area (such as the large rotary joints that point the ISS solar arrays and thermal radiator panels), or deactivating high power antennas that cause a radiation hazard to the crew when they enter specific areas. Most of these supporting tasks are performed by the crew inside the vehicle, called the intra-vehicular activity support crew, or by flight controllers on the ground. In either case, there may be timing constraints on performing the necessary supporting actions for a given task.

Some support system interactions could impact the timeline in the form of wait times. For instance, a new segment of thermal control tubing must be vented of its nitrogen pad before being connected to the flight system for the first time. In some cases, the crew may have to wait for this process to complete and, in other situations, it may be possible to continue with other tasks during the wait period.

d. Possibility of Suit Contamination

The ISS utilizes several highly toxic substances in its systems. This includes pure anhydrous ammonia and hydrazine propellants. In cases where the EVA crew must interact with these systems, there is a possibility of suit contamination from leaks. If an EMU suit comes in contact with a toxic substance, it must be decontaminated before it comes into contact with the ISS cabin atmosphere. MOD has developed a protocol called "bake-out" which is performed prior to airlock ingress and repressurization in cases where contamination is suspected. Bake-out requires the crew to use a brush to remove any crystals from the suit and then expose themselves to direct sunlight for a predefined period of time to heat any remaining crystals enough to sublimate off the suit. This is a fairly lengthy process which must be accounted for by scheduling tasks with a risk of toxic contamination early enough in the EVA to allow enough time for its completion in the event contamination occurs.

e. Break Out Points and Bingo Times

For tasks that could leave a component or system in an unsatisfactory condition if they are not completely finished, breakout points are identified based on the specific activities involved in a task and its predicted duration. A breakout point can be thought of as the point of no return during a task: a decision point to continue or abort the task based on how much time is left in the EVA. Tasks which cannot be segmented in this fashion, but carry the same risks if not completed, are assigned so-called "bingo times." A bingo time is the latest point in the EVA where the task can be started and still maintain a high probability of completion. Breakout points and bingo times are carefully evaluated as risk trades by the MOD team and the community of stakeholders.

7. Tandem Tasks

For the purposes of this thesis, we consider only the most common case of two-person EVAs. A substantial number of the possible tasks that could be assigned during these EVAs require both crew members to work together. The need for two crewmembers to perform a task can be driven by, for example, a need to maneuver or

hold in place unwieldy or massive equipment. The timeline must accommodate both crew members being in the correct location during the same time period to accomplish tandem tasks.

8. Tool Requirements

Most tasks require that the crew use one or more tools. Many tools have been developed for use by EVA crewmembers, ranging from pry-bars to zero-torque bolt drivers and cameras. Deployment, transport, and use of tools are important factors in EVA planning. Planners must ensure that the crew has the right tools packed in their bags before leaving the airlock, that tool sharing is accounted for if required, and that tool movements and temporary stowage are properly handled.

9. Subdivision of Tasks

Part of the heuristic nature of current EVA planning is in the subdivision of tasks. A given task may contain one single objective but require many steps to complete. These sub-tasks are not strictly defined by default and their nature may be optimized by the planner throughout the development and training process. A simple example of subdivision can be observed in the LEE R&R (Latching End Effector Removal and Replacement) EVA summary timeline (shown as the third timeline in Figure 2). Depending on how detailed the program customer task data is, the planner may receive several sub-tasks or just one task, "Replace Failed LEE," as an input for this timeline. In the case where few detailed tasks are given, the planner must subdivide the larger tasks into steps which can then be planned individually. Examination of the LEE R&R timeline in Figure 2 shows there are multiple individual tasks identified to perform the objective and demonstrates the level of subdivision that is typically done by the planners.

The subdivision may be based on any number of factors just a few of which follow. Tasks may have natural break-points that could be used to subdivide them, such as moving to a new worksite, changing tools, or altering tether points. Other drivers may be based on the elimination of wait times that could be part of larger tasks (for instance, if only part of the task requires two crew members).

C. PROCESS IMPROVEMENT AREAS

MOD's flight controllers and planners often find themselves in the position of having to call a halt to a seemingly never-ending string of minute improvements to their plans and products with the phrase "better is the enemy of good enough." Ultimately, they are preparing for events that will happen on a rigid schedule. Missions and operations will not wait while the next incremental improvement is made. In this light, it is difficult to claim that improvement is needed with respect to EVA planning. The success of currently employed methods cannot be disputed. NASA has approached, and no doubt in some cases achieved, a maximization of the potential of each EVA opportunity. However, we believe there are ways to improve the process while also making it faster. Below, we detail some of the challenge and risk areas for the current process.

1. Cost, Schedule, and Experience Requirements

The process described in Section B is very labor-intensive as every step in it is completed by hand. This, in turn, demands highly skilled and experienced personnel. The typical EVA lead planner from MOD has five to ten years of training and experience. This caliber of engineer is a very costly resource. Additionally, since the structure of the organization is such that the same group of people perform the planning, crew training, and all other stages of EVA development, there is a zero-sum game aspect to work planning. Any off-loading of effort from the highly skilled MOD workforce can free them up to perform the work that truly demands their expertise. In other words, applying their expertise to *evaluating* plans rather than *drafting* them. Developing and refining high level timelines needed every time tasks, durations, or priorities are updated could be streamlined. Automation to a degree that can allow the expert to focus on the outcome rather than the tedious work of task ordering and basic constraint de-confliction would be a valuable benefit. Moreover, as the process involves several iterations of these development phases, the payoff of automation is multiplied.

2. Production Speed

As a corollary to the labor-intensive nature of current EVA plan development, the process is slow to navigate. This has several impacts at different points in the process. Early on, it prevents the evaluation of many different timeline options. Later in the process, it restricts the ability to deal with late-breaking changes or perturbations.

There is constant change occurring throughout the EVA development cycle, especially as it relates to ISS, a continuous mission. This change can take the form of priority changes, new tasks being added to a plan, other tasks being deleted (for lack of hardware or other reasons), or even change of crew members who will be performing the EVA. Further, support equipment can fail or be lost, keep-out zones can be added or changed, or changing environmental factors such as solar beta angle can force changes to tasking or timing. Some of these factors can impact an EVA just days prior to planned execution (see Section II.E.2 for a more complete explanation of uncertainty in sunlight conditions).

The Big 12 EVAs discussed earlier are a prime demonstration of the utility of a rapid prototyping capability for EVA planning. Even though the pump module replacement conducted in 2010 shows that the current process is capable of dealing with such situations, the ability to create multiple evaluation-ready draft overview timelines in minutes or hours would significantly help the planning team.

Even more impactful are changes that occur in real-time during an EVA. Many times, problems with a task early in an EVA may prevent the completion of tasks planned for later. Other times, the crew gets ahead of the timeline and there may be free time that can be utilized. The MOD team does plan for these situations, but in order to maximize the efficiency of EVAs, a full accounting of all possible changes must be done. There is rarely time for such a complete examination. Choosing which tasks to add to an EVA that is ahead of schedule or delete from one that is behind is hardly done haphazardly, but the decisions could be more informed if basic planning decisions could be tested rapidly.

3. Limited Ability to Assess Options

Flowing out of the first two limitations is the fact that only a small number of options can be evaluated for a given EVA. In some cases, there are only a few tasks on the program's list and slotting them into a given EVA is easily done. However, in cases where there are more tasks than could fit into a single EVA (or multiple EVAs if a series is being planned), the experts cannot assess all possible combinations of task selection. Once tasks are selected, their ordering during the EVA is the next decision. Once again there are cases where this is self-evident, but also many where discretion can be applied. Even a relatively limited list of tasks can have a very large number of combinations, far too many for a planner to investigate comprehensively. An automated tool for optimal task selection and ordering would improve the quality of the resulting EVAs by combining the two decisions into one.

In summary, such a tool would be a very powerful ally in negotiations with the program about task prioritization and placement. It would also find much use throughout the iterative process of plan development and even possibly in real-time operations.

D. RESEARCH GOALS

The goal of the research documented in this thesis is to investigate the feasibility of utilizing combinatorial optimization to improve the efficiency of EVA timeline development. Specifically, we seek improving the current EVA planning process in: (1) the time required to develop a timeline, (2) the thoroughness of trade-space evaluation, and (3) the verification (or simplification) of rule and constraint compliance. We have introduced the planning process as one that involves substantial effort and broad scope. It requires much in the way of individual expertise, experience, and hands-on development. Our goal is not to create a solution that nullifies this expertise, but rather enhances it by alleviating the considerable burden of developing initial timelines and by allowing the evaluation of many more potential combinations of tasks than is possible today. We further intend to understand how useful such a tool might be throughout the planning

process and its many iterations from first timeline through the execution phase. Any examination of the benefits of a solution must also investigate its limitations and we include this in our study as well.

We also intend that by focusing our solution on workload reduction for the EVA planners rather than attempting to create a turn-key plan development tool, our model will meet with greater acceptance in the user community. This is critical if any result of this research is to be pursued to assist in future EVA planning.

II. EVA PLANNING MODEL

This chapter details the development of the EVA Planning Model (EPM). We begin with a survey of some classical problems and techniques in the operations research literature to put the EVA planning problem in context and to justify our approach to the problem. Requirements for the model are outlined in Section C, and addressed in the EPM's formulation developed in Sections D and E.

A. MODEL CONTEXT

The goal of the EPM is to create the optimum EVA plan, which to the first order, is the one that maximizes the priority of scheduled tasks within the allowable time. The EVA planning problem has three major sub-parts: selecting which of the available tasks will be placed into the timeline, assigning those tasks to one of the crew members, and ordering the tasks. Clearly, these three sub-problems cannot be addressed individually in series because each one must be considered with respect to the other two. We must also understand that priority alone does not dominate the decision making in EVA planning. It coexists with efficiency which can be conceptualized in pseudo-units of priority per time unit per task.

Solving the problem of translating customer requirements (in the form of tasks and relevant task data) into the best possible EVA timeline can be informed by utilizing aspects of and concepts from several classical combinatorial optimization problems in the operations research literature. This section puts the EVA planning problem into context by drawing parallels to these classical problems.

1. Knapsack Problem

In its simplest form, the knapsack problem assumes a given a set of items, $j \in \{1, 2, 3, \ldots n\}$, where each item j has a value, p_j, and a weight, w_j. The problem is to determine the optimal combination of items to maximize the total value which can be

carried in a knapsack of limited weight capacity, c. Binary variables, x_j are introduced to indicate whether or not a given item has been selected. The mathematical formulation is as follows (from Martello, 1990):

$$\begin{aligned} &\text{Maximize} \quad Z = \sum_{j=1}^{n} p_j x_j \\ &\text{s.t.} \qquad \sum_{j=1}^{n} w_j x_j \le c, \\ &\qquad\qquad x_j \in \{0,1\}, \quad \forall j \end{aligned}$$

The planning drivers for EVAs can vary as discussed in Chapter I. In situations where the goal is to construct the best possible EVA from a collection of prioritized tasks identified by the program, task selection is a critical part of the solution. The knapsack problem is a perfect analogue to this and provides us with a guide for the task selection sub-problem.

We can adapt the knapsack problem by substituting tasks for items, priority for value, and duration for weight. Our constraint is the maximum allowable length of the EVA. It can also be associated with a situation where an existing EVA timeline has some spare time, or "white space," available and we must select from amongst a group of candidate tasks to fill it.

This adaptation allows us to use the knapsack problem formulation as a base upon which to build our task selection model. We must, of course, still concern ourselves with several intricacies of task selection imposed by the remaining two intertwined sub-problems.

2. Travelling Salesman Problem

The travelling salesman problem (TSP) applies so naturally to a variety of business and travel endeavors that it has been contemplated since long before operations research became an organized field. Published non-mathematical formulations of the problem date back to at least 1832 (Schrijver, 2005). As summarized by Laporte (2010), it considers the problem of a salesperson whose region contains n cities which must all

be visited exactly once before returning to the home city. The goal is to minimize the total travel distance or cost while still visiting each city. The problem can be visualized more easily as a simple network graph as in Figure 4. The distance between each city pair (i, j) is denoted by $L_{i,j}$. Travel distance is equal between two nodes regardless of travel direction and all nodes are connected. The path taken by the salesperson through this network is called a tour.

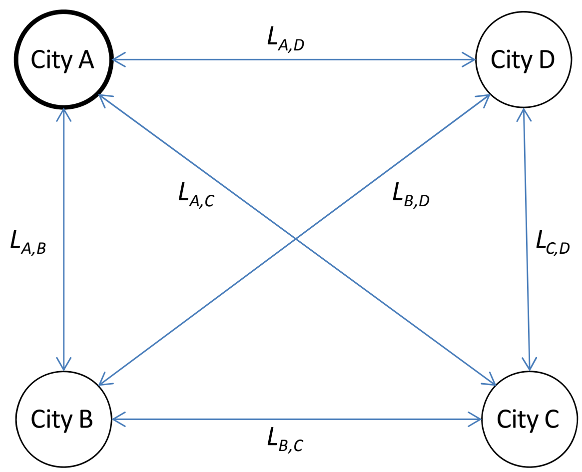


Figure 4. Basic travelling salesman problem network

Routing is a major factor in EVA task selection, assignment, and scheduling because the ISS is a large structure with widely distributed worksites. Since each astronaut must physically move from their current location at any time to the location of their next assigned task, there is a time penalty associated with scheduling adjacent tasks at locations separated by long distances. While this aspect of the EVA planning problem is a textbook instance of the TSP as described above, it has several considerations that make it a unique variation of the simple TSP. Figure 5 shows a network model more appropriate for the EVA case.

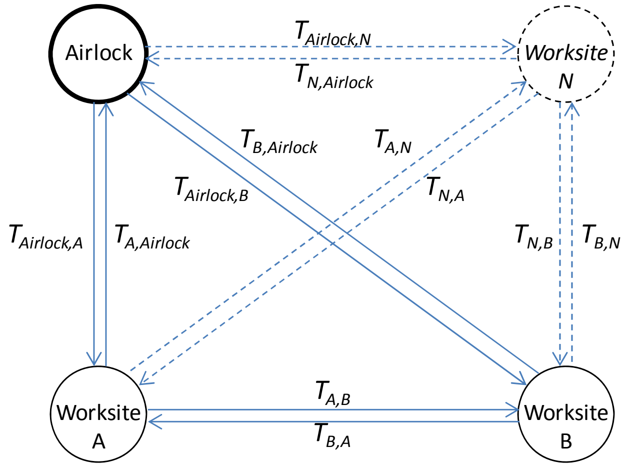


Figure 5. EVA planning problem as an asymmetric TSP network

There are several noticeable differences between the network arrangements in Figures 4 and 5 that hint at some of the complications of applying TSP methods to optimizing crew movement. Note that the EVA problem includes two time costs: the time to move (or translate) from node i to j, and also the time required to perform the task at j. The arc costs, $T_{i,j}$, in Figure 5 are the sum of these two costs. Observations about the EVA problem as it relates to the TSP follow:

(1) Asymmetry. The EVA network in Figure 5 is asymmetric. There may be a different cost to travel between two nodes depending on which direction is traversed. This is because the EVA case is expressed in units of time, which is the travel "cost" of the EVA planning problem (as opposed to distance or money). Even if we ignore the task duration caveat noted above to separate translation time and task duration, the time required to travel between any two nodes in the EVA case is still asymmetric. The physical translation time between worksites, which may or may not be aided by robot arm support, is the sum of the movement time and the time it takes for the astronaut to properly restrain himself at the new location. This can involve setup and ingress of an adjustable portable foot restraint, configuration of a body restraint tether, or a number of other tasks. Since the crew support interfaces can vary by worksite, the travel cost of a given arc in Figure 5 is dependent on the destination node and thus the EVA problem involves an asymmetric TSP (ATSP).

(2) Dynamic Nodes. We do not have a static set of nodes (worksites) in our network. Worksites are associated with tasks and task selection is part of the overall problem. If we stipulate that all tasks must be completed, the EVA routing sub-problem reduces to a generic ATSP network, but we need to allow for tasks to be omitted if they are not part of an optimal solution so a complete network does not exist until the problem is completely solved. Figure 5 depicts this with the dashed node, N .

(3) Multiple Agents. We have two crew members visiting the worksites associated with the tasks, thus making this a multiple TSP, with the additional complication that some tasks require synchronization of both crew members. Therefore, the goal is not simply to divide all the worksites or tasks among the two crew members so that each is visited or performed once and only once.

(4) Redundancy. An EVA plan does not restrict repeated visits to the same location. The basic travelling salesman problem stipulates that each node (with the exception of the source node) be visited only once. This constraint is not appropriate for EVA for various reasons: task precedence relationships and the inclusion of tandem tasks may stipulate that a worksite be visited several times. Alternatively, we may never visit certain worksites or perform certain tasks. To constrain movement (or task selection) such that each worksite must be visited exactly once would severely limit the usefulness of the resulting EVA plans.

(5) Multiple Task Locations. Although an EVA plan can be generally visualized by use of network diagrams as in Figure 5, the interweaving of tasks and locations makes the true meaning of the nodes ambiguous. Since tasks are inherently associated with worksites, a node could ostensibly represent a worksite location or a task; however, some tasks occur at multiple worksites and thus a crewmember may arrive at a particular node to begin a task and leave from a different node at its completion.

(6) Time Windows. Constraints on lighting, interfaces with support systems, ground communications, and other concerns can force tasks or worksites to be off limits at certain times. These type of constraints are partially represented in the time-window variant of the travelling salesman problem, but non-standard specifications of those

constraints are required in the EVA case as will be discussed later in this document. Figure 5 denotes the existence of time windows with dashed arcs.

(7) Precedence. Precedence relationships exist between many tasks. This results in what amounts to a combination of time windows but the restriction extending to pairs (or sequences) of nodes rather than just single nodes.

3. Dynamic Programming Problem

Imagine the EVA sequencing sub-problem as one of slotting tasks into a series of stages, $k \in \{1, 2, 3, \ldots |K|\}$. This conception of the problem is depicted in Figure 6: nodes represent possible tasks, and each arc has a transition "cost" equal to the time it takes to translate from one worksite to another, plus the time it takes to perform the second task. Since we know that every EVA starts with airlock egress and ends with airlock ingress, those nodes are fixed, and the problem aims to select which task is placed into a given stage in order to create a sequence that minimizes completion time of all tasks, similar to a shortest path problem. All other nodes in the network are based on the tasks available and are a result of the task selection sub-problem.

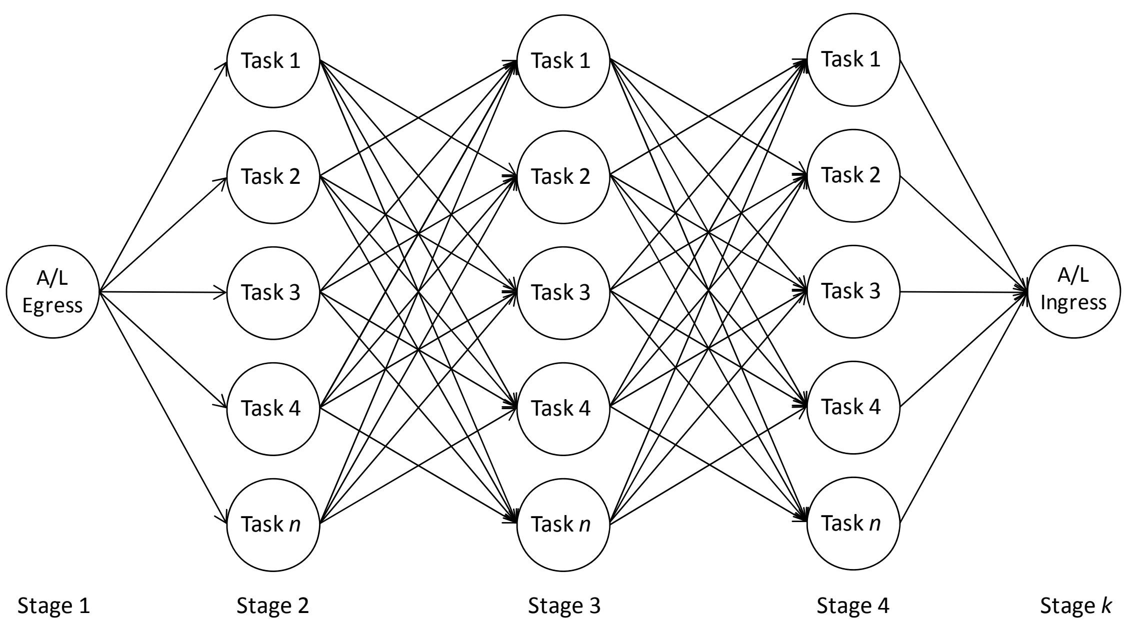


Figure 6. EVA planning problem as a shortest path network with stages

It is worth noting that the EVA planning problem, when conceived as described above, resembles a dynamic programming problem. The characteristics of these problems (see, e.g., Winston (1987)) are: (1) the problem can be divided into stages with a decision required at each stage; (2) each stage has a number of states associated with it; (3) the decision made at any stage describes how the state at the current stage is transformed into the state at the next stage; (4) given a current state, the optimal decision for each of the remaining stages must not depend on the previously reached states (known as the principle of optimality, see Bellman, 1954); and, (5) there must be a recursion function any stage, k, and state, i, that provides costs associated with the next stage, $k+1$. Figure 6 shows that we are able to divide the problem into stages and that the tasks (which include task specifications such as location, duration, etc.) represent the states for each stage. The decision of which arc to follow from each state defines a transition to the next stage and state.

However, there are several factors that make the actual EVA problem more difficult than that of Figure 6. The first complicating factor is that the number of stages in the network is not a constant, but varies based partly on both the number of tasks under consideration and their durations. Our desire to allow all tasks to be represented as states in all stages of our network, to be eliminated from subsequent stages, $k+1, k+2,...K$, if selected in stage k, would violate the principle of optimality. Each stage should contain any task which has not already been completed (or ruled out by other constraints such as task precedence). That dilemma also threatens the possibility of creating a recursion function. Finally, additional complications arise given that there are two crew members performing tasks simultaneously during an EVA.

4. Job Shop Problem

Among the classical problems in operations research, the job shop is a well-known model employed for sequencing tasks. This section discusses the basic tenets of the job shop problem and its application to EVA planning.

a. General Description of Job Shop

The job shop problem, is primarily a scheduling optimization problem formulated for manufacturing, production, or similar operations (see, e.g., Nahmias (2009)). The generalized setup of the problem is a manufacturing floor or assembly line with machines that perform actions on "jobs" that arrive at the plant. Jobs have a duration (also called processing time) and a due date. This results in a need to identify the sequencing that will result in the most efficient use of resources.

b. Static and Dynamic Variants

The arrival pattern of jobs can be either static or dynamic. In the static scenario, all of the jobs are known and present when the analysis begins, thus the question of the processing order is simplified. In a dynamic scenario, jobs arrive at intervals throughout the analysis period. Arrivals may be in set intervals or random and based on a probability distribution. In the dynamic case, the job shop problem takes on the characteristics of a queuing model. More randomness can be encountered if the job duration is not deterministic.

c. n Jobs on m Machines

In its basic form, the job shop problem assumes that all jobs, n, arriving at the shop will be processed by all machines, m. The flow pattern of jobs can be dependent on precedence relationships, machine availability, processing times, and a host of other considerations. In the multiple machine case, each job may have a different duration for each machine.

A special case of the multiple machine shop is one in which some or all of the machines are interchangeable. In that case, any job can be processed by any machine of its type and jobs do not need to be processed more than once by identical machines. In that situation, minimizing idle time on the machines, called line balancing, is an important consideration.

d. Sequencing Rules

At the heart of any job shop problem is the selection of sequencing rules. Nahmias (2009) identifies the following commonly used sequencing rules:

(1) First-come, first-served. Jobs are processed in the order they arrive.

(2) Shortest processing time. The shortest duration jobs are performed first.

(3) Earliest due date (EDD). Jobs with the nearest due dates are performed first.

(4) Critical ratio (CR). A critical ratio is calculated for each job equal to the processing time divided by the remaining time until the due date as shown in the equation below. Jobs with the highest CR are performed first.

$$\text{CR} = \frac{\text{Processing time}}{\text{Due date - Current time}}$$

e. Performance Metrics

The measure of effectiveness used for a job shop solution can vary depending on its goals. Some metrics in common use are:

(1) Flow time and mean flow time. Flow time is the total time to complete a given job from its entry into the shop to its exit. Mean flow time is the average of the flow times for all jobs.

(2) Makespan. Measures the total time to complete all jobs.

(3) Tardiness. Calculated as the difference between the completion time and the due date. A positive number indicates the job has been completed after the due date.

f. Job Shop Applied to the EVA Planning Problem

Stripped down to its simplest form, the EVA planning process accepts tasks as inputs and produces as its output the most efficient sequence to accomplish those tasks. Next, we point out some significant differences between job shop problems and EVA planning.

The EVA planning problem, conceived as a job shop, is formatted as having static job arrival and two machines (crew members). Since, for the most part, any task can be assigned to either crew member, these play the roles of interchangeable machines performing parallel processing. This means the problem can be viewed as two separate single-machine job shops, albeit still subject to line balancing considerations. The situation is static because all tasks are identified up-front and so a time dependent arrival pattern and the resulting queue are not a factor. The result of these characteristics is that for the EVA problem, the focus shifts from the flow of tasks into and through the shop to the task allocation of the machines.

Another change in focus from the job shop problem is that, in EVA planning, tasks are defined by their priority and duration rather than by a due date. As task selection and assignment are both variables that work in concert with sequencing, our problem differs from a classical job shop in that ours does not force all tasks to be processed. One immediate impact of these subtle differences is that the constraints on the problem are not related to task due dates but rather to available machine time. The standard job shop time-to-completion based performance metrics of makespan, tardiness, and flow time become meaningless for a single EVA. Task due date and the time-based performance measures could be applied to a system designing a series of many EVAs, but the primary focus of this thesis is for single EVA planning.

The job shop problem nonetheless provides a basic framework for the single EVA scheduling problem. In particular, we intend to adapt the concept of sequencing rules to EVA planning. First, we must understand the subtle nature of the planning goals, two of which can be stated as (1) maximizing total task priority, and (2) maximizing priority per unit time during the EVA. The subtlety of the second goal is that, although an EVA is an activity of known duration, the task priority per unit time should be applied as a running value *throughout* the EVA, not just at its completion. This has great importance because of the possibility of early EVA termination or delays in tasks early in the timeline which may force tasks nearer to the end to be skipped. Both of these situations are outside the planner's control and result from unexpected events or

problems. Current planning heuristics mitigate these risks by scheduling high priority tasks as early as possible while maintaining overall efficiency. Any credible planning tool must address these considerations.

The above discussion suggests the EDD sequencing rule is a valuable concept when applied to EVA task scheduling. Task priority replaces due date to create a new sequencing rule based on EDD. We refer to this as "highest priority first" (HPF). HPF sequencing would result in scheduling tasks in descending priority order, which serves the purpose of rewarding the scheduling of higher priority items earlier in the EVA. HPF cannot be the final word on task sequencing, however, because it does not account for task duration (or the many other limiting constraints). It is clear that to ensure the best outcome, task duration must be accounted for in concert with priority. To help address this, we can borrow again from the job shop problem. Adapting the concept of the critical ratio to define a priority ratio (PR), we can bring task duration and available time into the fold. The PR should look at the EVA as a whole to divide the sum of all task priority values by the total available time (in terms of PET):

$$PR = \frac{\text{Total Task Priority}}{\text{Total Available PET}}$$

A combination of HPF and PR can be used to create an EVA which has the highest overall priority value, but also the highest priority per unit time throughout the EVA.

5. Summary

The EVA planning problem is clearly a hybrid of many common problems in combinatorial optimization and the operations research literature. While no one model approach addresses all of the requirements and goals of the EVA problem, aspects of each of them can be applied to assemble a combined model which addresses the three sub-problems of task selection, crew assignment, and task sequencing. Sections C, D, and E outline those needs and develop the EPM.

B. OTHER EVA PLANNING IMPROVEMENT EFFORTS

The EVA planning process has long been understood to be very time consuming for the planning experts. Attempts have been made to address this by applying advanced automation techniques to timeline generation.

1. Prototype Knowledge-based EVA Planning System

Notable among attempts to optimize the EVA planning process is a previous master's thesis by Bleisath (1995), then a member of the EVA planning group. That work developed an automated knowledge-based tool to create EVA timelines. The development focused on the scheduling of tasks and the ease of use of the resulting tool for the planners. It represents an EVA as a group of tasks that must be ordered optimally without addressing the question of task selection. Thus, it classifies the problem as a general job shop problem and utilizes heuristic search to approximate its solution.

Two major factors drove the direction of that research: (1) the approach had to be practicable using computer power that was severely limited compared to the systems in common use today, and (2) it was undertaken at a time before any ISS EVAs had been planned or executed, and so did not have the full benefit of experience that we presently have at our disposal.

Due to the limited computer resources available, formal mathematical programming was not considered a viable option, and the number of tasks that could be scheduled per EVA was relatively limited. As a result, the tool provides a somewhat limited, high-level output for EVA task sequencing (although it produces full timelines and includes an impressive amount of detail such as calculation of crew movement speeds in various configurations).

The model has a limited set of input data and constraints which includes:

- Task priorities
- Precedence relationships
- Concurrence relationships (e.g., tandem tasks)
- Manual task placement (e.g., planners have the ability to override portions of its output manually)

- Assignment of specific tasks to specific crewmembers

The tool developed by Bleisath produces impressive results but has not been in use by EVA planners due primarily to its omission of many nuanced constraints which have evolved throughout the operational history of EVA on ISS.

Advances in computer power opens the option of utilizing formal mathematical programming. In addition, the wealth of operational knowledge from 15 years of ISS EVAs has allowed us to understand what data is easily available and how major tasks may be split into many subtasks. We can include notably more detail and realism in our model as a result of these advantages.

2. Artificial Intelligence Based Planning Automation

A more recent, and continuing effort, performed by TRACLabs, Inc. with NASA funding, investigates the automation of spaceflight planning from a wider perspective. This work is focused on automating planning for all disciplines in human spaceflight, including EVA. Bonasso, Boddy, & Kortenkamp (2009) utilize an EVA-centric scenario to serve as a test case and example of their efforts in automated mission planning. Their work focuses on integrating NASA's in-development procedure representation language with artificial intelligence (AI) based planning tools.

A fascinating aspect of this research is that it delves to a much lower level of detail than we intend to do with EPM, but in the process are much closer to possible solutions to the sub-problem of task sub-division. Their starting point of using existing procedures to develop inputs for AI planners naturally leads to a focus on four things: (1) decomposition of tasks into smaller parts, called hierarchical task nets, (2) assessing the resources associated with tasks, (3) thinking of tasks in terms of beginning states and ending states, and (4) understanding the interaction between actors and the interoperability of systems involved with the execution of tasks. Figure 7 represents a typical hierarchical task net developed by TRACLabs to decompose an EVA task called *Remove CETA Light*. The figure highlights the differences in the planning level of EPM, which considers *Remove CETA Light* as a single task needing no further decomposition, to the high level of task dissection performed for the AI planner.

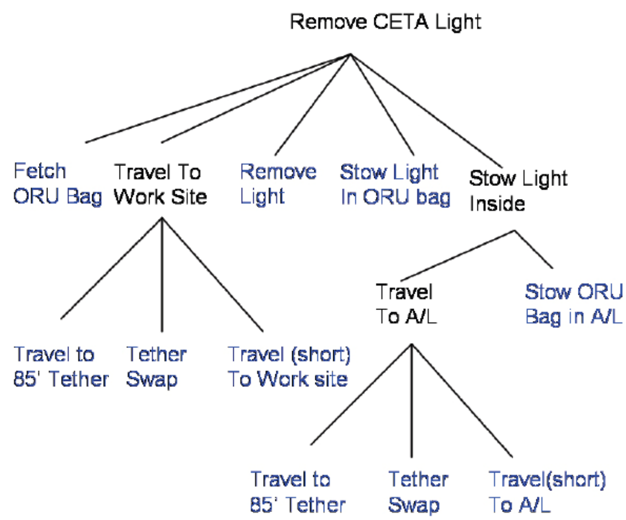


Figure 7. Hierarchical task net (from Bonasso, Boddy, & Kortenkamp (2009))

The ability to fully model the interoperability of systems and the interaction of different actors in the performance of a task is well beyond the scope of the EPM, as is the focus on resources. In many task decompositions, the leaves, or lowest level of the network may all be performed by different actors (flight controllers, EVA crew members, crew members inside the ISS, etc.). Further, the tracking of resources is very meticulous, including any and all countable resources that can be used, consumed, or produced by a given task. For the EPM, we understand time and tools or equipment are important resources (although tools are left to future refinements of the model), but do not attempt to track or constrain EMU oxygen levels or carbon dioxide removal system consumption as the automation tool does.

In the actual planning of EVA activities at the high level, the EPM employs optimization to select, assign, and arrange tasks whereas the planning system currently utilized by TRACLabs is driven wholly by heuristics with the human expert planner left to do any optimization. It is exactly this optimization that the EPM is intended to aid and thus there is possible synergy between the two efforts. One possible collaboration area is in sharing of the task database and resource database for future versions of EPM.

C. MODEL REQUIREMENTS

This section outlines the basic requirements of the EVA planning model including time and crew limitations, first order constraints, and outputs. Any requirements which are omitted or simplified will be discussed. The subsequent sections describe the details of the included requirements and show how they are being addressed.

1. Basic Summary Timeline Development

The EPM must accept input data from the user in the form of tasks and task attributes and output a summary timeline for a single EVA that can serve as a basis for evaluation by an expert planner. Creation of this timeline necessitates that the model selects tasks from a provided list and orders them in such a way as to maximize the priority value of the EVA. The model should then allow iteration to portions of the plan that do not meet customer or operational needs while holding the satisfactory part of the plan steady.

EPM output can be the basis for further evaluation, development, and training, as in Figure 1, or as supporting material for negotiations with the program customer regarding task priorities and/or expectations of task allocation to specific EVAs.

2. Task-Specific Conditions

The model should account for the conditions and special circumstances identified in Section I.B when generating EVA timelines. Subdivision of tasks and task synergy are not part of the model requirements at this time. The insight and intuition necessary to perform these functions is beyond the scope of a first-generation planning model. Certainly, though, the model can still aid a planner in subdividing tasks by providing optimal timelines throughout the process and making the impacts of any subdivisions more obvious.

3. Crew-Specific Adjustments

The model should account for differing crew skill levels and the desire to assign a specific crewmember to a specific task for any number of reasons (e.g., higher training or experience level).

4. Omissions

Although identified as important aspects of EVA planning, the EPM does not currently address tool constraints or subdivision of tasks (and as a result, break-out times). Neither is task synergy incorporated in the model. These capabilities involve significant complication well beyond the other rules and constraints handled currently by the EPM.

D. INPUTS

The EPM accepts inputs in the form of text files produced using templates in Microsoft Excel. These files and the data they contain are described below. All sample files shown are from the LEE R&R contingency EVA, the summary timeline for which is shown in Figure 2.

1. Task Data

For each task, the model requires the following data:

- Task name
- Task priority (in "value" units, where higher values indicate higher priority)
- Task duration if performed by EV1 or EV2 (in minutes)
- Task bingo time, if required (in minutes)

Each task also has a set of binary flags (1 if true and 0 if false) associated with it to indicate whether or not:

- Task is mandatory
- Task requires both crewmembers (tandem)
- Task carries the risk of toxic fluid contamination on the EMU suit
- Task has a limited set of legal time windows

- Task has a bingo time
- Task is the final airlock ingress

Table 1 is the input template for the data described above.

	Priority	DurEV1	DurEV2	Mandatory	Tandem	Airlock	Toxic	HasWindow	HasBingo	BingoTime
PVGF_Release_from_EP	5	5	6	0	0	0	0	0	0	0
P1_Worksite_Setup	5	30	33	0	0	0	0	0	0	0
Remove_CLA	5	10	11	0	0	0	0	0	0	0
Translate_Failed_LEE_to_ELC1	5	30	30	0	1	0	0	0	0	0
Spare_LEE_Prep	5	45	50	0	0	0	0	0	0	0
Stow_Failed_LEE_on_Temp_Stow_Ring	5	35	35	0	1	0	0	0	0	0
Retireve_Spare_Lee	5	40	40	0	1	0	0	0	0	0
Translate_Spare_LEE_to_P1_Worksite	5	30	30	0	1	0	0	0	0	0
Install_CLA	5	10	11	0	0	0	0	0	0	0
Install_LEE	5	30	30	0	1	0	0	0	1	270
LEE_FSE_Cleanup	5	9	10	0	0	0	0	0	0	0
Remove_LEE	5	40	40	0	1	0	0	0	0	0
Cleanup_Ingress	5	30	30	1	1	1	0	0	0	0
Egress_Setup	5	15	15	1	1	0	0	1	0	0

Table 1. Task input data template

Tasks that have time windows have additional data input requirements. In addition to flagging them in the above-mentioned template, the allowable time windows must be specified separately. For each such task, the following data are required (template shown in Table 2).

- Window, task joint identifier
- Start time of each window (in minutes, PET)
- End time of each window (in minutes, PET)

		tmin	tmax
w1	Egress_Setup	0	30
w1	Sample_Task	30	65
w2	Sample_Task	90	100
w3	Sample_Task	210	220

Table 2. Task-time window input data template

2. Precedence Relationships

Tasks with precedence relationships are specified in a separate input file via a predecessor-successor data structure. Tasks can be paired or chained with any number of other tasks to create unique and complicated relationships. Table 3 shows a typical precedence relationship input in the template.

Predecessor	Successor
P1_Worksite_Setup	Remove_CLA
Remove_LEE	Translate_Failed_LEE_to_ELC1
Remove_CLA	Translate_Failed_LEE_to_ELC1
Translate_Failed_LEE_to_ELC1	Stow_Failed_LEE_on_Temp_Stow_Ring
Spare_LEE_Prep	Retrieve_Spare_Lee
Translate_Failed_LEE_to_ELC1	Retrieve_Spare_Lee
Retrieve_Spare_Lee	Translate_Spare_LEE_to_P1_Worksite
Remove_CLA	Install_CLA
Remove_LEE	Install_CLA
Translate_Spare_LEE_to_P1_Worksite	Install_CLA
Install_CLA	Install_LEE
Translate_Spare_LEE_to_P1_Worksite	Install_LEE
Retrieve_Spare_Lee	LEE_FSE_Cleanup
Stow_Failed_LEE_on_Temp_Stow_Ring	LEE_FSE_Cleanup
Translate_Spare_LEE_to_P1_Worksite	LEE_FSE_Cleanup
Remove_CLA	Remove_LEE
P1_Worksite_Setup	Remove_LEE
PVGF_Release_from_EP	Remove_LEE
Stow_Failed_LEE_on_Temp_Stow_Ring	Retrieve_Spare_Lee

Table 3. Task precedence relationship input data template

3. Task Location Data

All tasks have associated worksites. Since some tasks can include a movement of the crewmember from one worksite to another, the model requires inputs for both the starting and ending location of each task (see Table 4). For convenience in our implementation, these two locations are entered in separate files.

Task	Initial Location	Final Location
PVGF_Release_from_EP	HTV	HTV
P1_Worksite_Setup	Columbus_WIF3	P1_Worksite
Remove_CLA	P1_Worksite	P1_Worksite
Translate_Failed_LEE_to_ELC1	P1_Worksite	ELC1
Spare_LEE_Prep	ELC1	ELC1
Stow_Failed_LEE_on_Temp_Stow_Ring	ELC1	ELC1
Retrieve_Spare_Lee	ELC1	ELC1
Translate_Spare_LEE_to_P1_Worksite	ELC1	P1_Worksite
Install_CLA	P1_Worksite	P1_Worksite
Install_LEE	P1_Worksite	P1_Worksite
LEE_FSE_Cleanup	ELC1	ELC1
Remove_LEE	P1_Worksite	P1_Worksite
Cleanup_Ingress	Airlock	Airlock
Egress_Setup	Airlock	Airlock

Table 4. Task location input data template

4. Translation Times

In order to convert the task location information into data useful for the EPM, the translation time between all worksite locations associated with a given set of tasks must be provided. The values are given in minutes and entered in a matrix format as seen in Table 5. Note that the matrix allows for different translation times depending on the direction traversed.

To / From	Airlock	HTV	ELC1	P1_Wrkst	Col_WIF3
Airlock	0	10	15	13	8
HTV	10	0	20	13	2
ELC1	15	20	0	13	20
P1_Wrkst	13	13	13	0	13
Col_WIF3	8	2	20	13	0

Table 5. Translation time input data matrix

5. Model Constants

The model utilizes several constants which can be adjusted if needed to change the parameters of certain planning constraints or to weight the relative prioritization of model objectives. These constants and their default values are:

- Priority Rank Weight [unitless], default value = 0.1
- Rank Start Time Weight [value/min], default value = 0.0001
- Total EVA length [minutes], default value = 390 minutes
- Latest bake-out start time [minutes], default value = 240 minutes

E. FORMULATION

This section introduces the mathematical formulation of the EPM as a linear mixed-integer program (MIP) that can be used to create or modify EVA summary timelines.

1. Mathematical Model

Sets:

J , set of tasks, where $\tilde{j}$ is the airlock ingress task

K , set of ranks (task sequencing order), where $K = \{1, 2, \ldots |K|\}$

C , set of crew members, where $C = \{\text{EV1, EV2}\}$

T , subset of J that requires two crew members. Note: $\tilde{j} \in T$

Q , subset of pairs of tasks, $(j, j') \in Q \subset J \text{ x } J$, where j precedes j'

M , subset of J comprised of mandatory tasks that must be completed regardless of priority. Note: $\tilde{j} \in M$

H , subset of J which carry the risk of toxic fluid contamination on EMU suit

L , subset of J which must be scheduled in time constrained windows, defined in set W

W, set of time windows defining allowable periods to perform tasks identified in set L

J^0, subset of L which cannot start at time zero (i.e., do not have a time window that includes time 0).

B, subset of J which has a bingo time constraint (i.e., task must be scheduled such that it will be completed by a certain time or it should not be attempted)

Data [units]:

$d_{j,c}$, duration of task j for crewmember c (for tandem tasks it should be made the same for both crew irrespective of their skills) [min]

p_j, priority value of task j [value]

ω^p, objective function weighting coefficient for task priority [unitless]

ω^s, objective function weighting coefficient for task start time [value/min]

$x_{j,j'}$, translation time between tasks j and j' (based on the final and initial locations for both tasks, respectively) [min]

λ, latest airlock ingress completion time (this is the maximum allowable EVA duration) [min]

δ, latest bake-out start time [min]

β_j, latest start time for task $j \in B$ [min]

$t_{w,j}^{\min}$, first allowable start time in window w for task $j \in L$ [min]

$t_{w,j}^{\max}$, latest allowable end time in window w for task $j \in L$ [min]

Decision Variables [units]:

$Y_{j,k,c}$, 1 if task j is selected in rank k for crewmember c, 0 otherwise

$S_{k,c}$, start time for rank k of crewmember c [min]

$U_{j,c}$, start time for task j for crewmember c [min]

$V_{j,j',k,c}$, 1 if task j' follows task j in adjacent ranks, k and $k+1$ for crewmember c, 0 otherwise

$R_{w,j,c}$, 1 if task j is scheduled in window w for crewmember c, 0 otherwise

Objective Function:

$$\text{maximize} \sum_{j\in J,k\in K,c\in C} p_j\left(1+\frac{\omega^p}{k}\right)Y_{j,k,c} - \sum_{k\in K,c\in C}\omega^s S_{k,c} \tag{1}$$

Subject To:

$$\begin{aligned} &Y_{j,k,c}\in\{0,1\}, \quad \forall j\in J,k\in K,c\in C \\ &R_{w,j,c}\in\{0,1\}, \quad \forall w\in W, j\in J,c\in C \\ &V_{j,j',k,c}\in\{0,1\}, \quad \forall j, j'\in J,k\in K,c\in C \end{aligned} \tag{2}$$

$$\begin{aligned} &S_{k,c}\geq 0, \quad \forall k\in K,c\in C \\ &U_{j,c}\geq 0, \quad \forall j\in J,c\in C \end{aligned} \tag{3}$$

$$\begin{aligned} &U_{j,c}\geq S_{k,c}-2\lambda(1-Y_{j,k,c}), \quad &&\forall j\in J,k\in K,c\in C \\ &U_{j,c}\leq S_{k,c}+2\lambda(1-Y_{j,k,c}), \quad &&\forall j\in J,k\in K,c\in C \\ &U_{j,c}\leq \lambda\sum_{k\in K} Y_{j,k,c}, \quad &&\forall j\in J,c\in C \end{aligned} \tag{4}$$

$$\sum_{j\in J} Y_{j,k,c}\geq \sum_{j\in J} Y_{j,k+1,c}, \quad \forall k\in K,c\in C \tag{5}$$

$$U_{\tilde{j},c} + d_{\tilde{j}} \leq \lambda, \quad \forall c \in C \tag{6}$$

$$U_{j,c} \leq U_{\tilde{j},c}, \qquad \forall j \in J, c \in C \tag{7}$$

$$\begin{aligned} &\sum_{k \in K, c \in C} Y_{j,k,c} \leq 1, \ \ \forall j \notin T \cup M \\ &\sum_{k \in K, c \in C} Y_{j,k,c} \leq 2, \ \ \forall j \in T \setminus M \end{aligned} \tag{8}$$

$$\sum_{k \in K} Y_{j,k,1} = \sum_{k \in K} Y_{j,k,2}, \ \ \forall j \in T \tag{9}$$

$$U_{j,1} = U_{j,2}, \ \ \forall j \in T \tag{10}$$

$$\begin{aligned} &\sum_{k \in K, c \in C} Y_{j,k,c} = 1, \ \ \forall j \in M \setminus T \\ &\sum_{k \in K, c \in C} Y_{j,k,c} = 2, \ \ \forall j \in M \cap T \end{aligned} \tag{11}$$

$$\sum_{j \in J} Y_{j,k,c} \leq 1, \ \ \forall k \in K, c \in C \tag{12}$$

$$\begin{aligned} &S_{k+1,c} \geq S_{k,c} + \sum_{j \in J} d_{j,c} Y_{j,k,c} + \sum_{j,j' \in J | j \neq j'} x_{j,j'} V_{j,j',k,c}, \quad \forall k \in K, c \in C \\ &V_{j,j',k,c} \leq Y_{j,k,c}, \qquad \forall j, j' \in J, k \in K, c \in C \mid j \neq j' \\ &V_{j,j',k,c} \leq Y_{j',k+1,c}, \qquad \forall j, j' \in J, k \in K, c \in C \mid j \neq j' \\ &V_{j,j',k,c} \geq Y_{j,k,c} + Y_{j',k+1,c} - 1, \qquad \forall j, j' \in J, k \in K, c \in C \mid j \neq j' \end{aligned} \tag{13}$$

$$\sum_{k\in K,c\in C} Y_{j',k,c} \le \sum_{k\in K,c\in C} Y_{j,k,c} \ , \qquad \forall j, j' \in Q \mid j, j' \in T \vee j, j' \notin T$$
$$\frac{1}{2}\sum_{k\in K,c\in C} Y_{j',k,c} \le \sum_{k\in K,c\in C} Y_{j,k,c} \ , \qquad \forall j, j' \in Q \mid j \notin T, j' \in T$$
$$\sum_{k\in K,c\in C} Y_{j',k,c} \le \frac{1}{2}\sum_{k\in K,c\in C} Y_{j,k,c} \ , \qquad \forall j, j' \in Q \mid j \in T, j' \notin T$$
$$\sum_{c\in C} U_{j',c} \ge \sum_{c\in C}(U_{j,c} + d_{j,c}\sum_{k\in K} Y_{j,k,c}) - 2\lambda(1 - \sum_{k\in K,c\in C} Y_{j',k,c}), \quad \forall j, j' \in Q \mid j, j' \notin T \tag{14}$$
$$\frac{1}{2}\sum_{c\in C} U_{j',c} \ge \frac{1}{2}\sum_{c\in C}(U_{j,c} + d_{j,c}\sum_{k\in K} Y_{j,k,c}) - 2\lambda(2 - \sum_{k\in K,c\in C} Y_{j',k,c}), \quad \forall j, j' \in Q \mid j, j' \in T$$
$$\frac{1}{2}\sum_{c\in C} U_{j',c} \ge \sum_{c\in C}(U_{j,c} + d_{j,c}\sum_{k\in K} Y_{j,k,c}) - 2\lambda(2 - \sum_{k\in K,c\in C} Y_{j',k,c}), \quad \forall j, j' \in Q \mid j \notin T, j' \in T$$
$$\sum_{c\in C} U_{j',c} \ge \frac{1}{2}\sum_{c\in C}(U_{j,c} + d_{j,c}\sum_{k\in K} Y_{j,k,c}) - 2\lambda(1 - \sum_{k\in K,c\in C} Y_{j',k,c}), \quad \forall j, j' \in Q \mid j \in T, j' \notin T$$

$$U_{j,c} \le \delta - d_{j,c} \ , \qquad \forall j \in H, c \in C \tag{15}$$

$$U_{j,c} \le \beta_j - d_{j,c} \ , \qquad \forall j \in B, c \in C \tag{16}$$

$$\begin{aligned} &\sum_{w\in W} t^{\min}_{w,j} R_{w,j,c} \le U_{j,c} \le \sum_{w\in W}\left(t^{\max}_{w,j} - d_{j,c}\right) R_{w,j,c} \ , \qquad \forall j \in L, c \in C \\ &\sum_{w\in W} R_{w,j,c} \le \sum_{k\in K} Y_{j,k,c} \ , \qquad \forall j \in L, c \in C \end{aligned} \tag{17}$$

$$Y_{j,k,c} \le U_{j,c} \ , \qquad \forall j \in J^0, k \in K, c \in C \tag{18}$$

2. Model Description

Equation (1) is the objective function of the EPM. The objective is to maximize the total priority value of tasks selected, and to maximize the priority per unit time throughout the EVA. Indirectly, by pushing tasks earlier when possible, the latter should

minimize early idle time during the EVA (excluding the idle time for an EV waiting for the other crewmember before airlock ingress). The objective finction is broken into two distinct terms to accomplish these goals.

Examination of the first term reveals that it is a variation of the knapsack objective formulation combined with the HPF and PR concepts derived from the job shop problem as discussed in Section II.A.4. Tasks are selected, assigned to a crewmember, and placed into a series of sequential ranks, $k \in \{1, 2, 3, \ldots |K|\}$. Each of the selected task's priority values contribute to the total objective value, but those values are decreased by a factor that is inversely proportional to their assigned rank number. This results in a penalty for placing tasks of equal priority into later ranks. It can be easily proven that, all else being equal, a task with higher priority value will be preferred for a lower rank after adjusting priorities with the $(1+{\omega^p}/{k})$ factor.

The second term in the objective function serves the purpose of imposing a penalty on unnecessary gaps between rank start times (and thus between task assignments). This has three effects: (1) to push tasks as early as possible in the EVA (helping to minimize idle time), (2) to minimize the duration of an EVA that has fewer than the maximum number of tasks, and (3) to enforce a job shop style line balancing between the two crew members.

The two constants, ω^p and ω^s, are values which establish the relative importance of the task selection by priority and early scheduling, respectively.

The constraint equations that follow are organized into multiple groups, each with a single associated equation number. In cases where the group as a whole is referenced, we use the given equation number for the group (x), whereas the y-th explicit expression within that group will be referenced in the format (x.y).

Equation (2) defines the three types of binary decision variables and Equation (3) defines the rank and task start time variables as being non-negative. Equation (4) establishes the relationship between rank start times and task start times. The start time for any task is set equal to the start time of the rank for which it is slotted. If the task is

not scheduled, the associated start time is unconstrained. The constant 2λ is used as it represents an upper bound to all allowable values of $U_{j,c}$. Additionally, all task start times are constrained to occur before latest airlock ingress time. Equation (5) stipulates that no empty ranks can exist prior to a rank which is assigned a task. This is required to ensure that translation times are properly accounted for later (in particular, in Equation (13)). Equation (6) forces the airlock ingress task (identified as $\tilde{j}$), which is always the final task of an EVA, to be completed no later than a pre-specified maximum EVA duration of λ, while Equation (7) ensures that the airlock ingress is the final scheduled task by eliminating any task start times after it.

Equation (8) prevents the repeated selection of tasks for both solo and tandem tasks. Equations (9) and (10) provide tandem task constraints such that a tandem task must be scheduled for both crewmembers or not at all, and that, if scheduled, start time of tandem tasks must be the same for both crewmembers. Mandatory task assignment is handled by Equation (11), forcing all tasks flagged as mandatory to be selected. It includes a coverage of solo and tandem mandatory tasks. Equation (12) prevents any conflicts associated with oversubscribing ranks. Each crewmember can have no more than one task assigned to each rank.

The group of constraints given in Equation (13) are related to crew movement between tasks. Translation time between task worksites is accounted for by exploiting the fact that Equation (5) disallows skipped ranks. Thus we know that tasks slotted into ranks k and $k+1$ for a given crewmember must be adjacent in time. The index j' is introduced to allow us to represent two independent tasks from set J in the same equation. Binary variable $V_{j,j',k,c}$ is introduced to allow a linear expression indicating that a transition between two specific tasks, j and j' occurs. Equations (13.2) - (13.4) ensure that $V_{j,j',k,c}$ takes a value of one if and only if task j is scheduled in rank k and task j' is scheduled in rank $k+1$ for crew member c. Once the translation order is established, Equation (13.1) constrains the start time of the next rank to include the previous rank's task duration and the appropriate translation time, $x_{j,j'}$.

Equation block (14) handles task precedence for the general case and several special cases. Firstly, Equations (14.1) through (14.3) ensure that a successor task, indicated by j', cannot be selected if the predecessor task has not been selected. The remaining equations constrain the start time of successor tasks to be after the completion time of any predecessors. If j is never completed, then $U_{j',c}$ is unconstrained, thus j' will never be scheduled if j is not scheduled, but j may be scheduled even if j' is not. The multiple versions of these expressions in Equation block (14) are required to handle all permutations of tandem and solo tasks among tasks with precedence relationships.

Equation (15) handles tasks flagged as having a possibility of EMU contamination with toxic materials and forces them to be completed prior to the latest bake-out time, δ. Note that bake-out requires a period of sun exposure for the EMU suit and is therefore dependent on sunrise and sunset times. Since there is a sunrise and sunset every 45 minutes at the orbital velocity of the ISS and many factors (including some unplanned factors) contribute to a variability of the crew's workday in relation to orbital day and night, the phasing between sunlight conditions and PET cannot usually be known until relatively close to the time of EVA execution. Fully optimizing the bake-out constraint through the setting of δ is difficult during the planning phase, which can occur months prior to the actual EVA. A conservative approach to establishing the bake-out start time would be to simply set δ at a level that guarantees a sufficient bake-out regardless of orbital sunrise and sunset times. This worst case would prompt the user to set $\delta = \lambda - d_{\tilde{j},c} - d_{\delta,c} - x_{j,\tilde{j}} - 45$, that is the EVA end time minus the combined duration of airlock ingress, the bake-out activity, the translation time between the hazardous task and the airlock, and a 45 minute pad for worst-case day/night phasing.

Equation (16) constrains the start time of tasks which have been flagged as having a bingo time. These are tasks which must be completely finished to avoid an undesirable configuration of the vehicle or have some other negative consequence if left incomplete. Each task in set B can have its own unique bingo time, so they are handled individually.

Equations (17) and (18) handle constraints for tasks with specific allowable task windows. Task windows are defined by the user with a beginning time and end time. For

a task flagged as having a time window, there is no limit to the number of allowable windows it can have. The model requires that the entire duration of the task fits into whichever window is selected. We introduce the binary decision variable, $R_{w,j,c}$, to denote selection of a specific window for a given task. Equation (17.1) constrains the start time of the task to be such that the entire task will fit in the defined window, while Equation (17.2) ensures that a window is selected if and only if the associated task has been selected. Equation (18) handles the special case of tasks with time windows that do not include PET = 0 minutes. Specifically, it disallows the start time of the task to be 0 minutes if the task is selected.

3. Implementation

The EPM is implemented in the General Algebraic Modeling System (GAMS) (Brooke et al., 2012) and all EPM runs described in this research are solved using CPLEX (GAMS/CPLEX, 2012) as a solving engine, on a desktop computer equipped with an Intel Core i7 CPU with eight processor cores running at 2.67 GHz and 6 GB of RAM.

A typical instance of EPM, such as black-box test case 1d, described in detail in Chapter IV, has approximately 19,000 constraints and 6,800 binary variables. Solve time for an optimal solution (at 0% optimality gap) ranges between 2 minutes and 18 hours.

III. MODEL TESTING AND VERIFICATION

This chapter describes the testing approach used to verify the EPM and presents model results. We employ verification techniques to provide thorough vetting of the model's correctness. Note that while verification is crucial for the EPM, full validation is not addressed here. This stems from the fact that the EPM has been built specifically to address the requirements in Chapter II, where any planning requirements that are deemed too complicated for the initial development of the model have been relaxed or omitted. Accordingly the model testing presented in this work seeks to demonstrate EPM at the proof-of-concept level, striking a balance between actual problem requirements and capabilities for practical use in EVA plan development.

A. METHODOLOGY

A full quantitative evaluation of the quality of the EPM in the traditional sense is not possible at this time. This is a result of several factors: (1) there is no established metric available to compare the quality of one EVA plan to another, (2) EVA planning relies heavily on heuristic approaches, and (3) decisions made in finalized EVA plans are not typically documented in a form that allows us to know which alternatives were considered and why they were rejected.

The manual nature of EVA planning is the biggest barrier to the creation of an autonomous EVA planning tool. It is also the most problematic aspect of approaching the question of measuring the output quality of even our basic EPM. Of course, many of the decisions involved in planning an EVA relate to which tasks will be included and the order in which they will be scheduled, but many more are related to the sub-division of tasks. Tasks may be sub-divided for myriad reasons, including, but not limited to: optimization of task locations to best utilize tether points, handholds, and permanent or moveable work fixtures, the tools required, and the body positioning or approach path for the crew. These complexities have been omitted from the EPM in order to simplify it

enough to make its development practical within this study. While this simplification is necessary to limit the scope of model development to a feasible size, it also rules out a strictly quantitative testing standard.

Given the lack of an ultimate quality metric, we focus our testing strategy on verifying that the implemented features execute as expected. The question of verification is by no means a simple one because the optimization model includes many nested logical conditions to account for constraints. Very few of these constraints are mutually exclusive, making testing a significant challenge. To develop a credible verification testing plan that remains manageable, we look to the field of software engineering. In this way, we view the EPM MIP formulation as a series of logical “if-then” statements as in a standard computer program. Each constraint (or group of constraints with a particular joint function) becomes a branch in the logic tree of the program that (when combined with all the others) comprises the EPM.

One potential approach to test such a program is exhaustive testing, wherein we test every possible logical combination in the model to ensure, ostensibly, that no errors remain undetected. Even in a very simple program with a small number of if-then constructs, exhaustive testing is an exceedingly daunting proposition and that for large or complex software systems it is effectively impossible. Exhaustive testing is a form of "white-box" testing which "is predicated on close examination of procedural detail. Logical paths through the software and collaborations between components are tested by exercising specific sets of conditions" (Pressman, 2010, p. 484). White-box testing provides exactly what we need to verify a model like the EPM and thus forms an important part of our testing strategy.

Our methodology is based on these guidelines suggested by Davis (1995): (1) tests should be planned before testing begins, (2) testing should start "in the small" and progress toward "in the large," (3) the Pareto principle applies to software testing (80% of errors will likely be traced to 20% of the program components), and (4) exhaustive testing is not possible (as cited in Pressman, 2010). EPM testing is accomplished in three phases which progress in scope from single elements to the entire model. We begin with unit testing of the individual components, move on to white-box testing of logical

sequences or processes, then to “black-box” testing. Black-box testing is not concerned with the internal workings of a software element, but rather focuses on its ability to produce expected outputs from known inputs. Black-box testing will provide the ultimate measure of the acceptability of the model as a whole and provide insight as to the feasibility of further development of the EPM into an operational tool.

B. UNIT TESTING

Throughout the development of the EPM, unit testing was constantly performed to verify functionality of individual components. The purpose of unit testing is to examine the basic building blocks of the model. The goal is to create test cases that exercise the smallest components while also reducing interaction with other segments as much as possible. See Tables 6 and 7 for documentation of the unit tests and their results.

Unit Test Number	Test Configuration		Expected Output	Test Result
	Test Goal	Test Setup		
0	Verify solo tasks can be scheduled	Input set of solo tasks with no special constraints. Total task time < available PET. All translation times equal.	All tasks scheduled	Pass
1	Verify no uneccesary idle time in output	Same as case 0	No idle time is included between any tasks	Pass
2	Verify translation times are accounted for	Same as case 0. Translation times between all locations are unique.	Translation times are correct and accounted for	Pass
3	Verify crew member assigment is optimized (a)	Same as case 0	Task assignment is split between crew members such that they have relatively equal total task+translation durations	Pass
4	Verify crew member assigment is optimized (b)	Same as case 0 but with all tasks having equal priority. All tasks have a duration of 10 minutes if assigned to EV1, half of the tasks have a duration of 30 minutes if assigned to EV2.	All tasks with duration difference assigned to EV1	Pass
5	Verify crew member assigment is optimized (c)	Same as case 4 but with all tasks having a duration of 10 minutes for EV1 and 30 minutes for EV2.	Task assignment is split between crew members such that they have relatively equal total task+translation durations	Pass
6	Verify tandem tasks can be scheduled	Same as case 0 but with at least 1 tandem task(s) in input set.	All tandem tasks scheduled for both crew members at the same PET	Pass

Table 6. Unit test configurations and results (unit test numbers 0–6)

Unit Test Number	Test Configuration		Expected Output	Test Result
	Test Goal	Test Setup		
7	Verify EVA PET is limited to specified duration	Input set of solo tasks of equal duration, unique priority, and no special constraints. Total task time >	EVA duration is limited to no more than the specified limit	Pass
8	Verify highest priority tasks selected	Same as case 7.	Tasks included in EVA to fill all available PET, excess tasks omitted based on priority (lowest are omitted)	Pass
9	Verify mandatory tasks are selected	Same as case 7 but with the lowest priority task flagged as mandatory.	Mandatory task scheduled at the expense of a higher priority task	Pass
10	Verify bingo times are adhered to	Same as case 9 but with the mandatory task assigned a bingo time.	Mandatory task is scheduled such that completion is prior to the bingo time	Pass
11	Verify bake-out times are adhered to	Same as case 9 but with the mandatory task flagged as toxic.	Mandatory task is scheduled such that completion is prior to the bake-out time	Pass
12	Verify time windows are adhered to	Same as case 9 but with the mandatory task given a specific time window.	Mandatory task is scheduled such that completion is within the specified time window	Pass
13	Basic task predence is adhered to	Same as case 0 but one task is assigned a predecessor.	Successor task is scheduled after associated predecessor is complete	Pass
14	Verify in-task translations are accounted for	Same as case 2 but for test task, assign different initial and final locations.	Translation times for test task properly account for different starting and final location	Pass

Table 7. Unit test configurations and results (unit test numbers 7–14)

C. WHITE-BOX TESTING

As pointed out in the previous sub-section, ad hoc testing became an important part of the process in real-time. As new capabilities were added to the model, simple impromptu tests were performed to ensure the model performed acceptably. Although these tests were not formally organized or documented, they provided valuable insight about where errors may reside in the logic. Based on this experience, we are able to empirically confirm the application of the Pareto principle, specifically related to portions of the model related to precedence relationships. We also found that errors tended to lurk where constraints intersected, for example precedence relationships between solo and tandem tasks.

Exhaustive testing of even this part of the model, as pointed out, is nearly if not wholly impossible. The number of test cases needed to evaluate all possible combinations of constraints is astronomical. In fact, the number of test cases is unbounded since there is no limit to the number of tasks (and associated attributes) that can be fed into the model. As such, we utilize the concept of basis path testing for the EPM. Basis path testing is a form of limited white-box testing commonly used for software programs with large logical control structures. To perform this type of testing, we first conceptualize the EPM as a series subroutines comprised of if-then statements. We then create control flow graphs for the subroutines and determine all possible logical paths through the graphs. These paths are referred to as a basis set and by creating test cases for each basis set, we ensure that each logical path within the subroutine will be exercised at least once with the minimum number of test cases (Pressman, 2010). While it is certainly possible for errors to slip though this testing, the technique provides a very attractive return on investment in terms of testing efficiency. The number of test cases required to complete basis path testing is given by the cyclomatic complexity of the subroutine's control flow graph. Calculating the cyclomatic complexity, $V(G)$, from the graph can be accomplished by simply counting the regions bounded by the edges and nodes in the graph (plus the region outside the graph) or by using one of the calculations below:

$$V(G) = E - N + 2$$
$$V(G) = P + 1$$

In the first expression, E is the number of edges and N is the number of nodes in the flow graph. In the second expression, P is the number of predicate nodes. A predicate node is a node which contains a decision and thus has more than one edge exiting from it.

Figure 8 shows the control flow graph for the precedence relationship portion of the EVM. All three methods above yield $V(G) = 13$ and thus the basis set contains 13 independent paths. This defines the number of test cases that must be run to test every part of the subroutine at least once. The flow graph is built from the perspective of a specific task, j, which is considered by the model for placement in a timeline. It shows

the multiple factors that play into scheduling a task with predecessors, including whether feasible start times (notated by the shorthand "U" in the graph) exist. This routine is used to establish if task j can be scheduled and to define when it can be scheduled. Assuming the task *can* be scheduled, there is no guarantee that it *will* be scheduled, the routine simply allows the rest of the optimization model to consider the task alongside all other candidates, while observing the timing limitations placed upon it by its precedence relationships.

One notable exception from the flow graph is a check if task j is flagged as mandatory. This is omitted because the model will exit without a solution in the case of a mandatory task that is impossible to schedule for any reason. Since we know such an input configuration will cause the model to fail to complete, there is no need to include it in the graph.

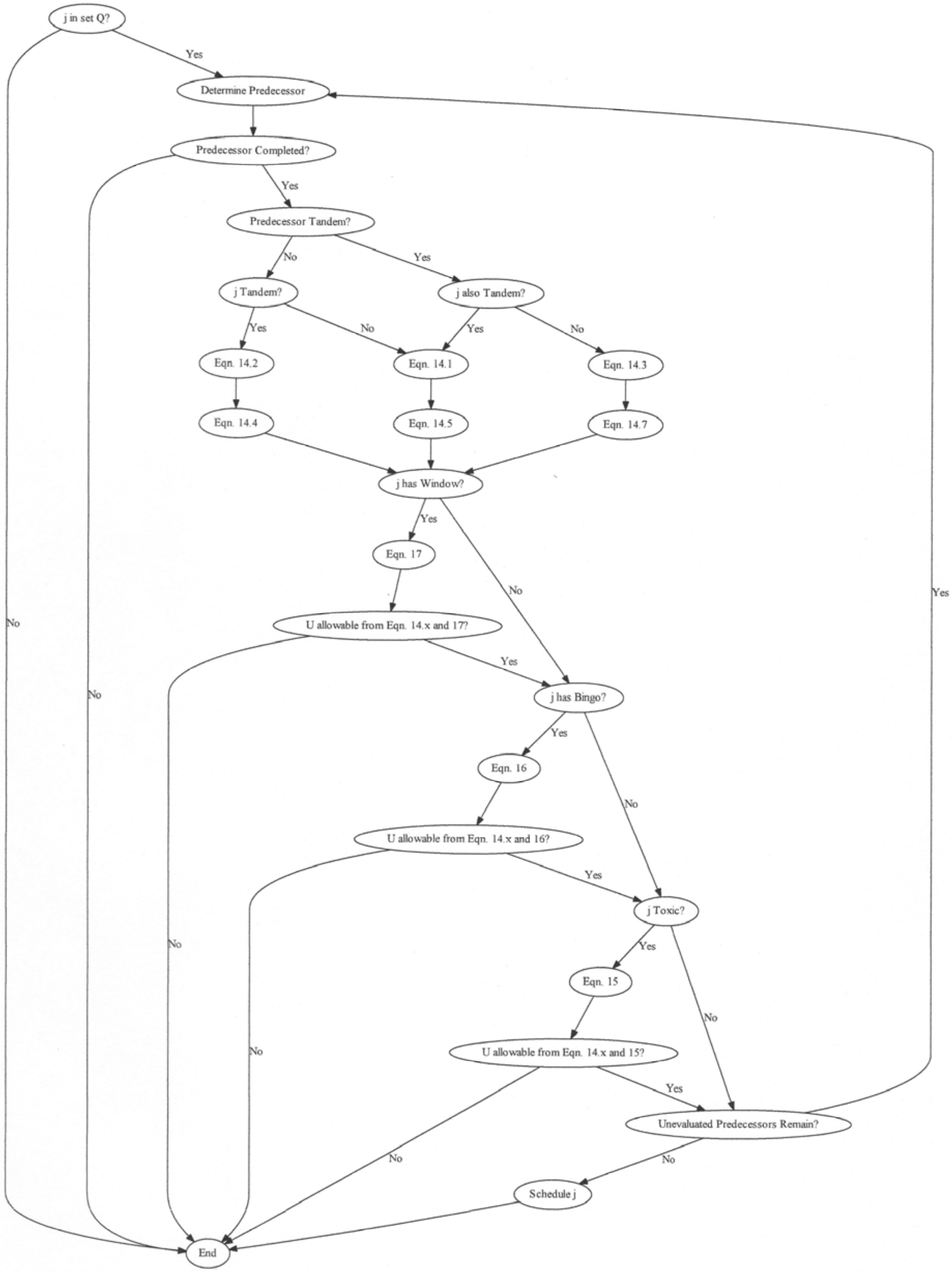


Figure 8. EPM precedence relationship control flow graph

Table 8 is the complete listing of all 13 path test cases comprising the basis set generated from the flow graph in Figure 8, their configurations, expected outputs, and results. The original test results (not shown) proved very useful as several errors in the model formulation and/or code were identified and corrected as a result of performing the test cases. Table 8 displays all tests passed after the errors were corrected.

Path Test Number	Test Configuration		Expected Output	Test Result
	Characteristics of Predecessor Task, j_P	Characteristics of Test Task, j_T		
0	n/a	Task j_T has no predecessors	Task j_T scheduled	Pass
1	Not complete	n/a	Task j_T not scheduled	Pass
2	Completed, Solo	Solo, no window, no bingo, not toxic	Task j_T scheduled after j_P	Pass
3	Two predecessor tasks, both completed	Solo, no window, no bingo, not toxic	Task j_T scheduled after both predecessors	Pass
4	Completed, Tandem	Solo, no window, no bingo, not toxic	Task j_T scheduled after j_P	Pass
5	Completed, Tandem	Tandem, no window, no bingo, not toxic	Task j_T scheduled after j_P	Pass
6	Completed, Solo	Tandem, no window, no bingo, not toxic	Task j_T scheduled after j_P	Pass
7	Completed, Tandem	Solo, infeasible window, no bingo, not toxic	Task j_T not scheduled	Pass
8	Completed, Tandem	Solo, feasible window, no bingo, not toxic	Task j_T scheduled after j_P, in valid time window	Pass
9	Completed, Solo	Tandem, no window, infeasible bingo time, not toxic	Task j_T not scheduled	Pass
10	Completed, Solo	Tandem, no window, feasible bingo time, not toxic	Task j_T scheduled after j_P, before bingo time	Pass
11	Completed, Solo	Tandem, no window, feasible bingo time, infeasible bake-out time	Task j_T not scheduled	Pass
12	Completed, Solo	Tandem, no window, feasible bingo time, feasible bake-out time	Task j_T scheduled after j_P, before bake-out and bingo times	Pass

Table 8. EVM precedence relationship basis set test configurations and results

D. BLACK-BOX TESTING

Black-box testing of the EPM is envisioned as a large scale exercise of the model as a complete unit. The purpose is to verify that the model can successfully create an optimized EVA timeline given a complete set of input data (as opposed to function-specific testing). The results of this testing are qualitative and by no means comprehensive, but this testing is a straightforward approach to evaluating overall model capability. Five test cases are generated for this purpose. Table 10, found at the end of this section, compares some key statistics between heuristic and EPM-generated timelines. In this section, "heuristic" refers to a solution manually generated by the author (not an EVA planner expert) using reasonable criteria derived from interviewing experts.

1. Black-box Case 1 Configuration

This case is intended to show optimization of task selection and ordering that may be time consuming or counterintuitive to a planner using manual and/or heuristic methods. Figure 9 is a graphical representation of this case. Each circle represents a task with the size of the circles representing the task's relative priority. The combined duration of the input tasks is greater than the available EVA PET, forcing some tasks to be excluded from the plan. As shown, tasks are split into three worksites with arrows indicating the translation times between worksites. All tasks have the same priority value save for one high-priority (but not mandatory) task. Task 5 has a priority value that is 1.5 times greater than each of the other tasks. The lower priority tasks are divided into two groups of co-located tasks. Worksites for both of these groups are close to each other and to the airlock, while the high-priority task is located far from all of them. All tasks are tandem and of the same duration. The green circles for Task 1 and Task 8 indicate they are mandatory, as these are the airlock egress and ingress tasks, respectively. The airlock egress task is constrained to occur first by the use of a time window.

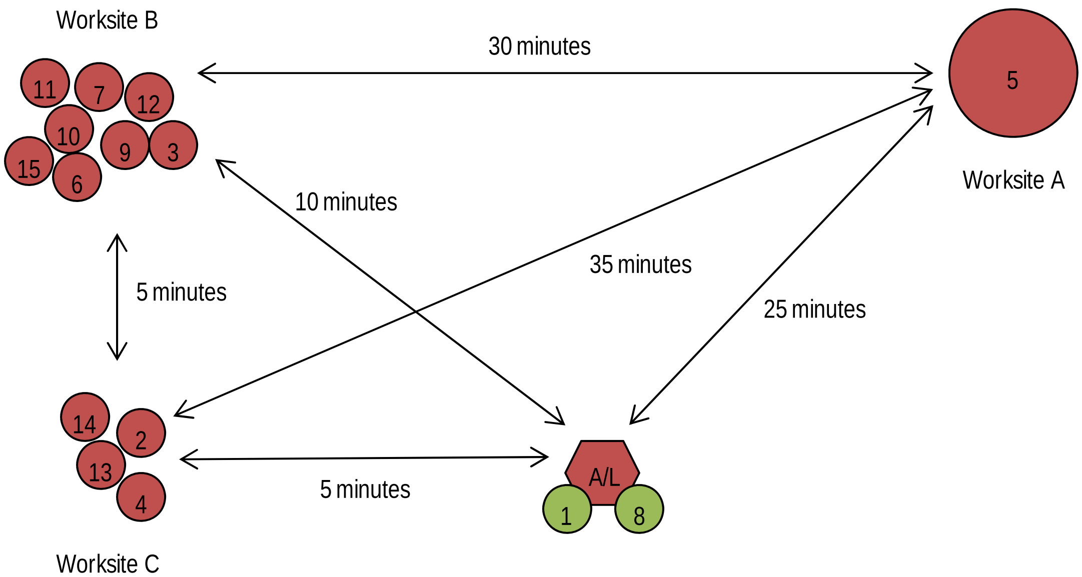


Figure 9. Black-box test case 1 configuration

The goals of this test case are to determine which tasks will be omitted from the timeline and how the model will sequence the tasks given the large time penalty for translating to and from worksite A to complete the high-priority Task 5. We will also compare the model result to a basic heuristic approach to the same inputs to examine the differences between the two results.

2. Black-box Case 1 Results

One heuristic approach to this test case might be to perform the highest priority task first, then move to worksite B, which has the largest concentration of tasks, perform as many of those as possible, then move to worksite C to perform tasks there if time allows before returning to the airlock. That approach results in the timeline shown at the top of Figure 10 and yields an objective score of 46.44 value units.

The EPM output is substantially different. Its output timeline is shown at the middle of Figure 10. With the priority ratio of 3/2 between Task 5 and the rest of the tasks, the model determines it is optimal to avoid the translation penalty to worksite A, and instead complete a greater number of the lower priority tasks at worksites B and C. While this may seem counterintuitive, the objective score of the EPM timeline is notably

better at 52.52 value units. Table 10 shows that the heuristic timeline, while including the highest priority task, omits twice as much cumulative task priority value as does the EPM solution.

One area where the EPM solution is clearly inferior to the heuristic solution is in solve time. The heuristic solution to this very simplistic case is fairly intuitive and can be created very rapidly by hand, while the EPM takes nearly 11 hours to arrive at an optimal solution. There are many possible causes for this poor performance, one of which may be the large number of identical tasks included in this test case. All tasks at each worksite are exactly the same in all respects. As a result, the MIP suffers from "symmetry," for instance, the EPM solution shows Task 2 performed first and Task 4 second, but swapping the order of those two tasks results in the same objective score. Another factor is the relatively close priority value between the highest priority task and the remaining tasks. In this case the solution is clearly much less obvious than the heuristic approach might lead one to believe.

Finally, we note that in authentic summary timelines, translations are not typically shown as separate activities. We have chosen to show them because they would assist an expert in assessing the efficiency of a timeline generated by the model. The tasks with the format "X Y-Z" in the summary timelines produced by the EPM are translations from location "Y" to location "Z."

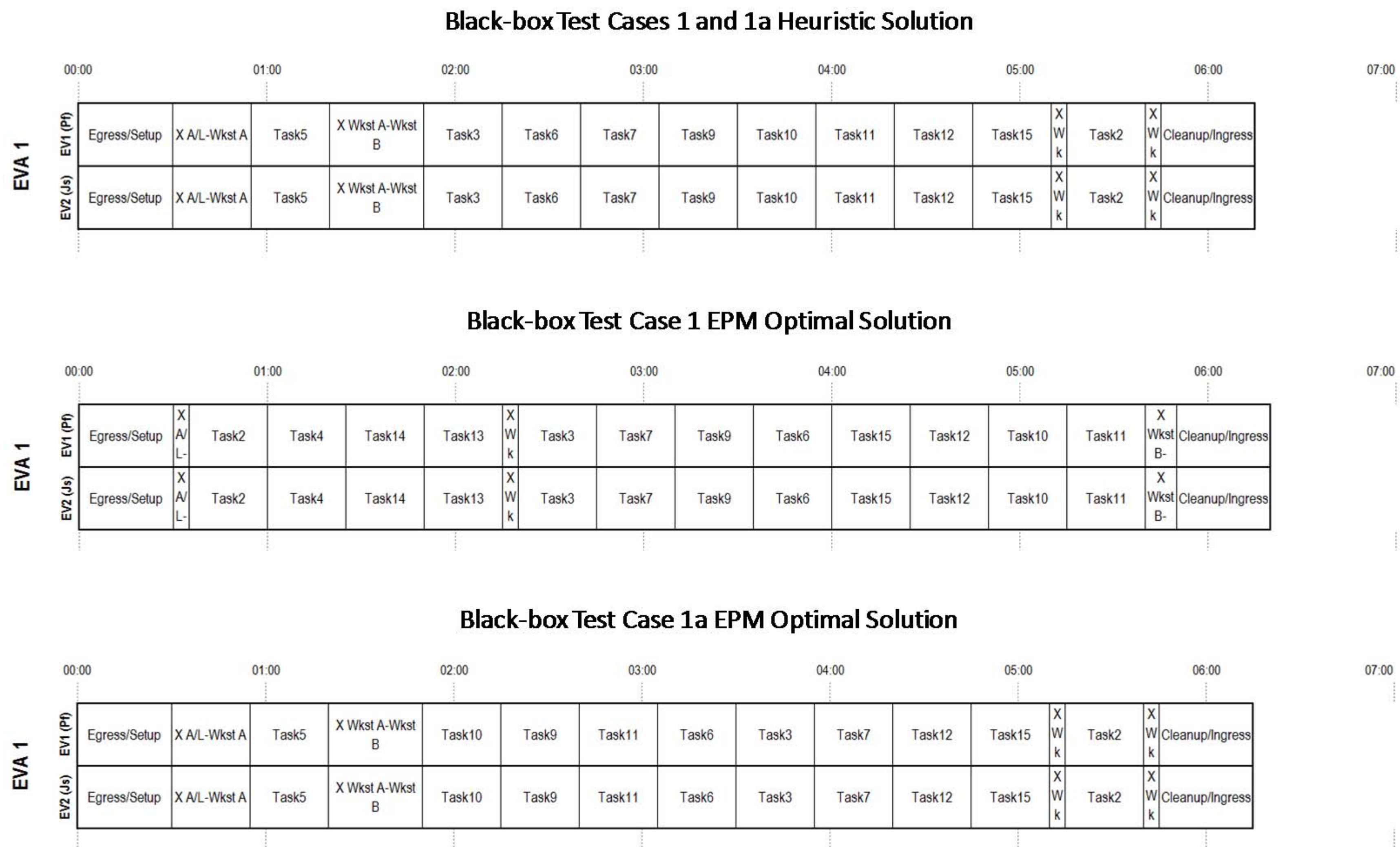


Figure 10. Black-box test cases 1 and 1a timelines

3. Black-box Case 1a Configuration

To see the effect of changing the priority of tasks, we increase the priority of Task 5 to triple that of the other tasks, leaving all other parameters the same as in Case 1.

4. Black-box Case 1a Results

This test configuration results in the same heuristic solution used in Case 1. The EPM solution (shown at the bottom of Figure 10) now matches the heuristic timeline exactly (note that the ordering of tasks at a specific worksite is interchangeable since all have identical properties). The EVA proceeds directly to worksite A to perform the high priority Task 5, then on to worksite B to complete all tasks there, and finally to worksite A where one task is completed before returning to the airlock. This problem proves much easier for the EPM to reach an optimal solution, taking only 22 minutes. The priority difference in this situation is enough to make Task 5 too valuable to omit, which in turn speeds up convergence to an optimal solution.

5. Black-box Case 1b Configuration

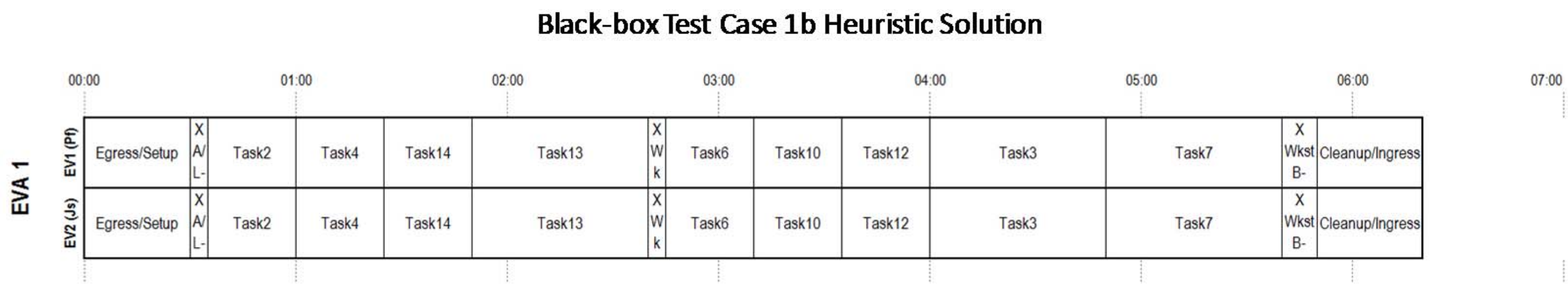
To see the effect of varying the duration of tasks, we modify Case 1 by making all odd numbered tasks (except Task 1, the airlock egress) twice the duration of the even numbered tasks (i.e., even numbered tasks last 25 minutes, odd numbered tasks last 50 minutes in this case). All other inputs and model parameters remain the same as those in Case 1.

6. Black-box Case 1b Results

The heuristic approach for this case consists of starting at the nearest worksite (C) and performing the shorter tasks first. Since it is clear that not all tasks will be performed, the only 50-minute task at worksite C (Task 13) is also performed before translating to worksite B. Task 5 is omitted because its longer duration and translation penalty outweighs its higher priority value.

The EPM solution also begins at worksite C, but omits Task 13 to move on to worksite B and perform the shorter tasks there instead. Both timelines accomplish the

same number of tasks, but the EPM scores a slightly higher objective score by scheduling more tasks earlier (the model timeline completes five tasks in the same time it takes the heuristic to perform four). Figure 11 shows both timelines.



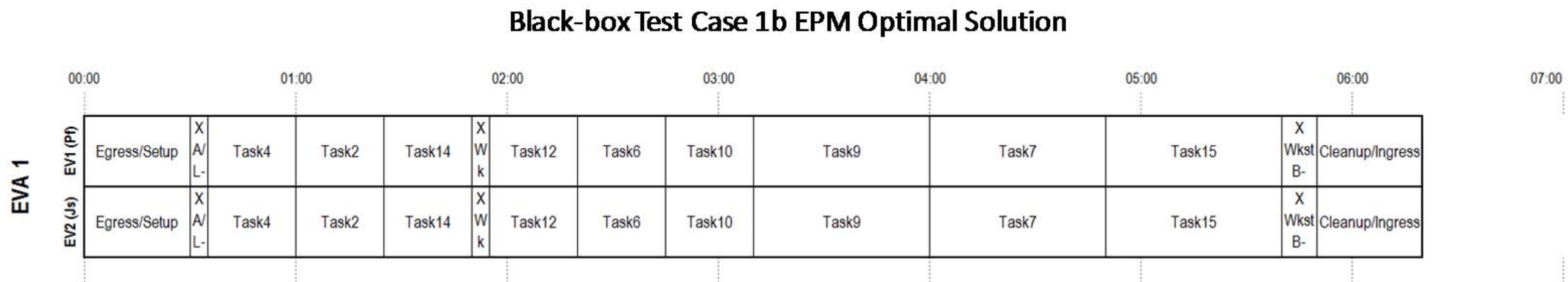


Figure 11. Black-box test case 1b timelines

7. Black-box Case 1c Configuration

To see the effect of employing both crew members independently, we have modified Case 1 by making all odd numbered tasks solo (except Task 1, the airlock egress), leaving the even numbered tasks tandem. All other inputs and model parameters remain the same as those in Case 1.

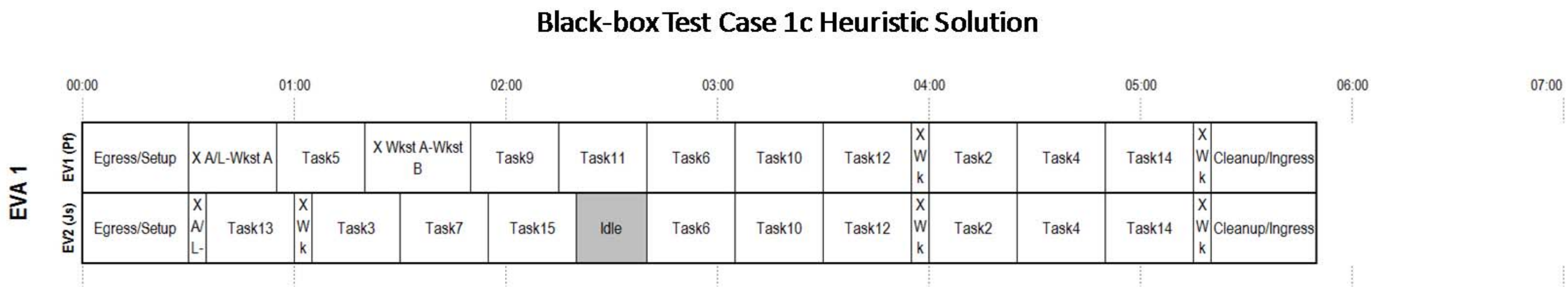
8. Black-box Case 1c Results

One special note about this variant of the test case is that making half the tasks solo activities means there is time to complete all the tasks during a single EVA. Task selection is not a factor and the optimization is related to sequencing only.

The heuristic solution for this case splits the crew immediately, sending EV1 to worksite A immediately to perform the highest priority task. EV2 translates to the nearest worksite (C), performs the only solo task at that location, then moves to worksite B to perform solo tasks until such time as EV1 can arrive. Both crew members continue to work on solo tasks until all are complete. In order to synchronize both crew members, an idle period must be incurred, after which they perform the tandem tasks together. Tandem tasks are completed first at worksite B, then worksite C. This solution yields an objective score of 43.42 value units. The heuristic and EPM summary timelines for this test case are shown in Figure 12.

The EPM optimal solution exhibits a subtly different approach to this case. It does not split the crew right away, but instead sends them both to worksite C to perform the three tandem tasks. It then leaves EV1 at worksite C to perform the remaining solo task there (Task 13), while EV2 translates to worksite B to perform a solo task. Upon completion of Task 13, EV1 translates to worksite B. This sequencing allows the crew member's timelines remain synchronized, and tandem tasks at worksite B may be initiated without any preceding idle time. When all three tandem tasks at this location are complete, EV2 is sent to worksite A to perform Task 5, while EV1 completes the remaining solo tasks at worksite B. The 20 minute idle time that must occur somewhere in this scenario is thus left to the very end of the EVA. This solution results in an objective score of 43.43 value units. While that is only slightly higher than the heuristic

solution, the practical difference is fairly dramatic in favor of the EPM solution. (The small difference indicates the weighing factors in the optimization model may need be revisited to ensure this highly desirable solution is more clearly differentiated from other solutions, but we do not perform that change here.) The EPM solution trades performing Task 5 earlier for moving the idle time penalty to the end of the timeline. It is very good practice to move idle time as late as possible. MOD planners have a motto that says "you should always leave runway in front of you," meaning "do not wait to do something if you might later regret not using that time." That is exactly what the EPM has done by delaying the idle time as long as possible. The good sense of this approach can be demonstrated if we imagine that during the execution of the heuristic timeline, for example, Task 11 took 15 minutes longer than expected. EV2, who had been idle waiting for the completion of Task 11, now is faced with another 15 minutes of idle time before any other tasks can be performed. In some cases, such a scenario could seriously compromise the success of an EVA.



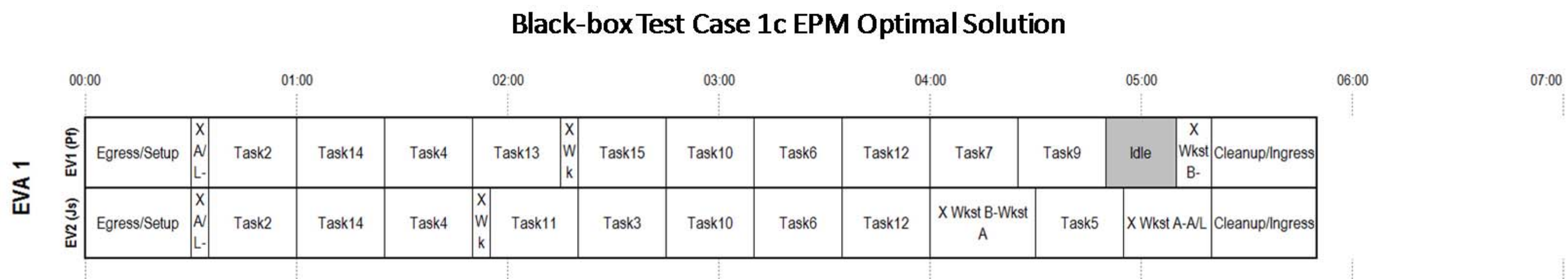


Figure 12. Black-box test case 1c timelines

9. Black-box Case 1d Configuration

Case 1d is intended to demonstrate the effect of defining allowable time windows for certain tasks. For this case we start with black-box test Case 1c and add the constraint that all tasks at worksite C must take place during orbital night. This type of constraint could be imposed because, for example, the tasks (or their locations) dictate that solar array rotary joints be parked (rotation is temporarily stopped). We can envision a scenario in which the ISS power consumption profile requires all solar arrays to be in sun tracking mode during orbital day instead of a less efficient parked position. In such a situation, the array may only be parked at night and our EVA timeline must comply with the requirement.

In addition to the timing constraint placed on the tasks at worksite C, we stipulate that Task 5 involves mating and/or de-mating toxic fluid connectors. This brings with it two more timing constraints: (1) the task can only occur during periods when the thermal environment has stabilized (to avoid large pressure changes in the fluid lines caused by temperature changes), and (2) the task's completion time must be such that sufficient time remains in the EVA to perform a bake-out if EMU contamination is suspected. The nature of Task 5 is not unprecedented; the ISS utilizes 100% anhydrous ammonia in its external thermal control system (NASA, 2011a) and connectors in this system must be manipulated during some EVA tasks, including some Big 12 contingency EVA tasks. In fact, leaks from exactly such a system during one of the pump module replacement EVAs in 2010 (NASA, 2010b) forced a bake-out to be executed to prevent toxic material from being introduced into the ISS cabin atmosphere (Harwood, 2010).

As discussed in Chapter II, there is a sunrise and sunset every 45 minutes at the orbital velocity of the ISS, thus the tasks at worksite C must be parsed into the windows that correspond to night periods. Further, the thermally stable conditions needed for Task 5 require that it not be scheduled during or immediately following a sunrise or sunset. The exact synchronization of the crew workday with sunset and sunrise times varies and is not typically known in exactitude until relatively close to the time of EVA execution. We estimate the night periods in terms of EVA PET windows in general, allowing for refinement when the true synchronization becomes clear. For this test case, we will use

the example orbital sunrise and sunset times in Table 9 to create our time windows. We have created the allowable time windows for Task 5 by assuming thermal stabilization takes 15 minutes following each sunrise and sunset and also included a five minute pad before sunrise and sunset as a safety margin. Recall that the latest bake-out time parameter, δ, is the latest PET at which toxic tasks must be completed. Here it is calculated using a 30-minute bake-out period and the orbital timing in the table.

Orbital Day/Night Times in PET (H:MM)		Thermally Stable Periods in PET (H:MM)		Latest Bake-out Time, δ, in PET (H:MM)
Sunset	Sunrise	Start	End	
0:15	1:00	0:00	0:10	5:05
1:45	2:30	0:30	0:55	
3:15	4:00	1:15	1:40	
4:45	5:30	2:00	2:25	
6:15	7:00	2:45	3:10	
		3:30	3:55	
		4:15	4:40	
		5:00	5:25	
		5:45	6:10	
		6:30	6:55	

Table 9. Time parameters for black-box test case 1d

10. Black-box Case 1d Results

Case 1d is a much more difficult one for a human planner to optimize because of the increased complexity. Utilizing basic heuristics, a feasible plan is created in relatively short order (40 minutes), but the EPM solution proves far superior. The model solution has a substantially higher objective score and again stands up extremely well to common sense analysis. The resulting summary timelines in Figure 13 demonstrate that while a human planner tends to think linearly about the problem, using small segments of idle time throughout the EVA to address the many timing constraints, the model is able to assess all possible options holistically. This allows the EPM solution to gather all the required idle time into one contiguous segment at the very end of the EVA, while the heuristic timeline includes five distinct idle periods. The result of the EPM's ability to consolidate this idle time is that it is able to accommodate all tasks and provide a full 35

minutes of usable time at the end of the EVA. The heuristic solution not only results in idle time that is not very useful due to its scattershot nature, but also forces the omission of one of the solo tasks at worksite B.

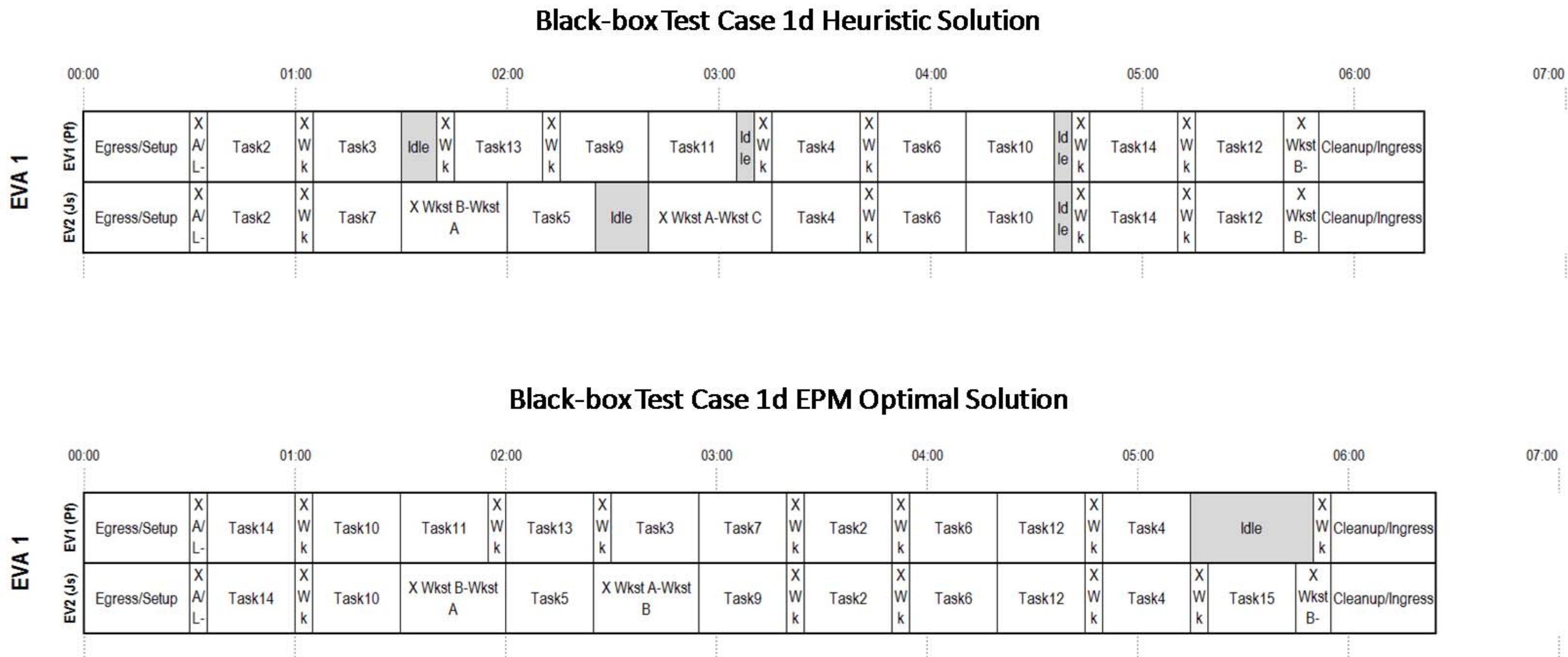


Figure 13. Black-box test case 1d timelines

11. Black-box Testing Summary

The black-box testing scheme confirms that the EPM produces credible results that match or exceed the results developed by a human (albeit not expert) planner in both objective value and common-sense assessment. The cases have been kept exceedingly simple in order to facilitate easy discussion and to allow a non-expert planner to make educated heuristic solutions in reasonably short time periods. Table 10 gives some comparative statistics related to the heuristic solutions to the test cases versus the model output.

Black-box Test Case Number	Objective Value		Priority Value of Omitted Tasks		EVA Duration (H:MM)		Idle Time Total (H:MM) / Type		Solve Time (H:MM)	
	Heuristic	EPM	Heuristic	EPM	Heuristic	EPM	Heuristic	EPM	Heuristic	EPM
1	46.44	52.52	6	3	6:15	6:20	0:00 / na	0:00 / na	0:10	10:54
1a	52.74	52.74	6	6	6:15	6:15	0:00 / na	0:00 / na	0:10	0:22
1b	40.34	40.35	9	9	6:20	6:20	0:00 / na	0:00 / na	0:15	0:10
1c	43.42	43.43	0	0	5:50	5:50	0:20 / Condensed mid-EVA	0:20 / Condensed at End	0:20	1:14
1d	41.31	43.36	2	0	6:20	6:25	0:40 / Scattered	0:35 / Condensed at End	0:40	3:55*

** Solution uses CPLEX "opportunistic" parallel mode (all other cases employ deterministic parallel mode)*

Table 10. Heuristic vs. EPM output comparison for black-box test cases

An unexpected benefit of the test series is that it exposed performance issues with the EPM model. Table 10 includes the solution times for each case and reveals that solution times have a large variation, but tend to be lengthy. Trivial changes to model inputs, such as changing the priority value of a single task, sometimes results in dramatic and unpredictable variations in solve time - even in deterministic modes (see below). To address the overall speed of the model as formulated, several CPLEX performance tuning techniques, advised in Gregory (2008), have been attempted for some of the cases (notably Case 1d). These techniques include the employment of up to seven parallel

threads in "opportunistic" mode, enabling aggressive probing, and utilizing the feasibility pump heuristic. Empirical evaluation of these modifications indicate some benefit is realized, although no attempt has been made to prove this fact. In using the parallel opportunistic mode (vice deterministic) solution times may vary even with identical inputs, making comparisons very difficult.

The black-box test series also exposes that the consolidation and placement of idle time is one of the most substantial strengths of the EPM. During initial development of the optimization model, this was not necessarily a specific goal. Demonstrating this capability has not been the goal of black-box testing, but its emergence in the test results is significant. There are substantial benefits to this capability that have real value in EVA planning.

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IV. PROOF-OF-CONCEPT EVALUATION

The testing program described in Chapter III proves that mathematical combinatorial optimization can be used to create EVA timelines that include a comprehensive consideration of trade-offs and constraints.

This chapter addresses the value of the EPM concept to develop timelines (and alternatives) for actual EVAs under current development, investigating the usefulness of an optimization model to alleviate some of the manual burden of creating initial and follow-on timelines. Although the number of test cases is very limited, we feel that these use-scenarios are representative of real-world planning situations and provide a valid basis for assessment of the EPM by expert planners.

A. METHODOLOGY

As discussed in Chapter III, evaluation of EVA timelines is largely subjective and by extension, evaluation of the EPM is also subjective. Understanding this, we have based our proof-of-concept assessment on (1) comparisons of EPM results to expert developed timelines and (2) expert opinions regarding EPM results and potential utility.

We have been able to work with EVA planning experts to gather the necessary real-world data to have the EPM independently create two EVA plans in parallel with their traditional development so the two results can be compared. Recalling that the planning process requires many "what-if" assessments and revisions to arrive at consensus regarding which tasks will be included in an EVA, when they will occur, and the opportunity costs (e.g., which tasks will be omitted or moved), we have modeled and evaluated reasonable alternatives to each of the cases.

We have also demonstrated the EPM to experts and obtained their opinions about its usefulness. The data are organized into sections, one each to describe the EVA development cases. Expert evaluations are summarized.

The reader is cautioned that many tasks and locations involved in the EVA development cases contain acronyms which are not defined unless their definitions are

important to a basic understanding of the scenario. In most situations, this level of detail is not needed and the acronyms are simply part of the task title. To avoid confusion, task names are presented in italics when discussed in the text.

B. LEE R&R EVA SCENARIOS

The LEE is a component of the space station robotic manipulator system (SSRMS) that allows the robotic arm to grab onto grapple fixtures mounted on large ORUs and the ISS structure. There are two LEEs on the SSRMS, one on each end. The LEE R&R EVA is a contingency EVA being planned in the event a LEE fails and needs to be replaced. A spare LEE is pre-positioned at a stowage location on the exterior of the ISS. Since this is a single-purpose EVA, the planning problem is focused on ordering of and crew assignment to tasks. Essentially, the tasks are steps in a larger "procedure." The combined duration of all the tasks is short enough to fit within a 6.5-hour EVA, eliminating the need to omit any tasks due to lack of time. There are, however, extensive precedence relationships associated with the tasks. Additionally, there are many tandem tasks and tasks that involve movement from one worksite to another (i.e., different starting and ending location). This scenario has only one task which is constrained by time: *Install LEE* is assigned a bingo time of 5:05 PET. The full set of raw data for this EVA scenario, referred to as LEE R&R EVA (original), has been provided by the lead planner (F. Sabur, personal communication, June 27, 2012), and can be found in Appendix A. The EPM solve time for the two scenarios in this section are somewhat capricious, ranging from 18 minutes for the original scenario to several hours for the alternate scenario.

There are very few possible feasible solutions to this EVA plan because of the high interaction level between all the tasks. Figure 14 shows the expert-generated, heuristic solution at the top and the EPM optimal solution in the middle. The EPM is successful in duplicating the expert solution.

To add some variability to this planning problem, some additional tasks unrelated to the LEE R&R activity are added. This is commonly done by the program customer when an EVA has extra time available, as this one does. The modified scenario is

referred to as LEE R&R EVA (alternate). We perform a second EPM run with three new tasks included whose characteristics are based on three tasks that were requested to be added to ISS EVA 18 three weeks before its execution. The alternate task data are shown in Appendix B. The EPM is successful in accommodating one of the three additional tasks while extending the EVA by 36 minutes over the baseline case (see Figure 14, bottom). The inclusion of more tasks is limited primarily by the long distances between the worksites of the LEE R&R and the new tasks.

Even though these results were fairly predictable given the constraint that all LEE R&R tasks must be completed before any of the new tasks could be scheduled, the EPM's ability to handle such cases has been successfully demonstrated.

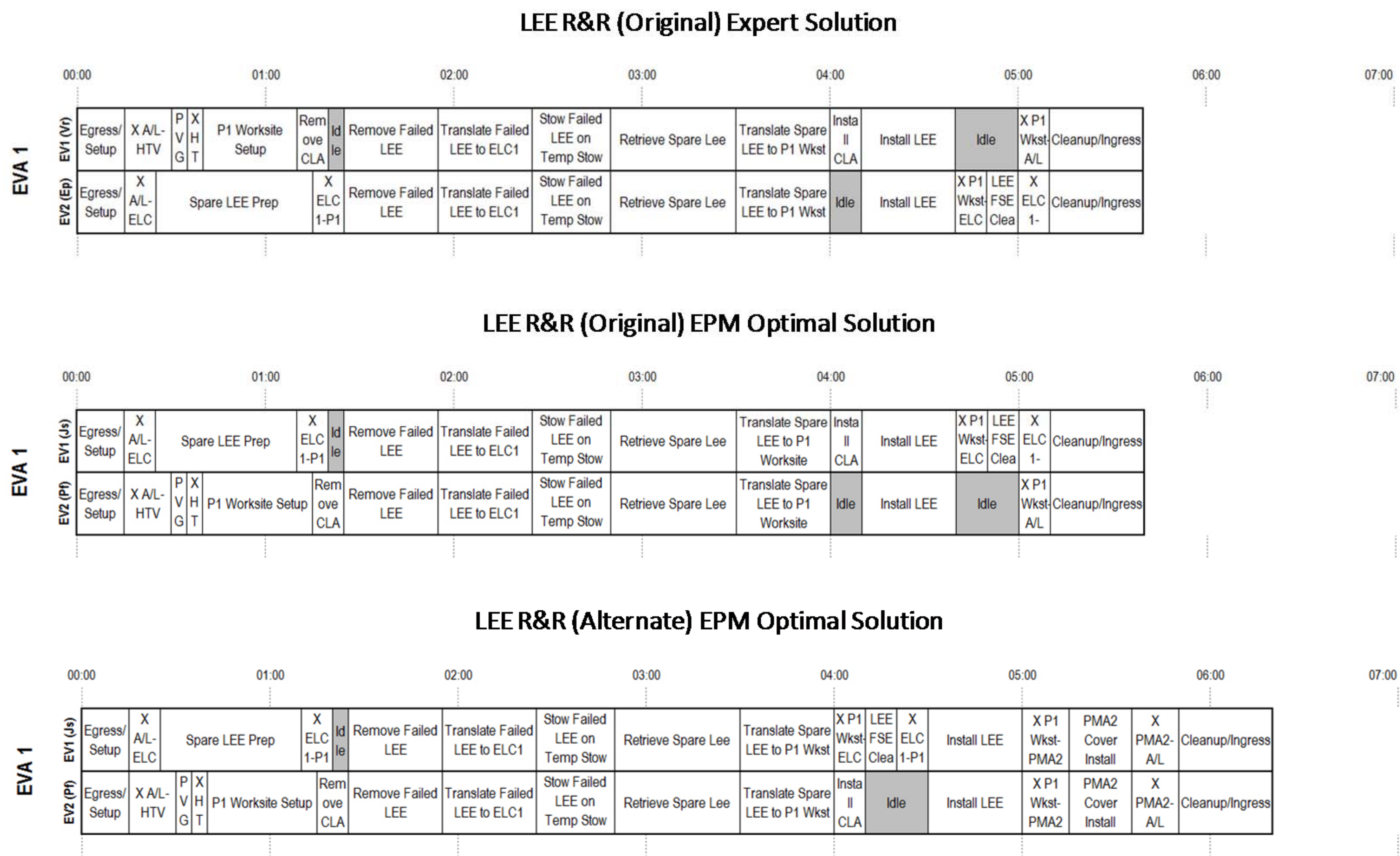


Figure 14. LEE R&R EVA timelines

C. EVA "A" SCENARIOS

EVA “A” is in the early planning stages for execution in 2013 or 2014. It is a more typical ISS assembly and maintenance EVA, driven by the need to accomplish a “to-do list” of tasks requested by the ISS program customer. This EVA represents a much different planning scenario than the LEE R&R. Here, the number and duration of requested tasks exceed the time available in a single EVA. All of the tasks are unique and independent, meaning no precedence relationships exist, and all tasks are solo. Two tasks requested for this EVA have time window constraints. The first, *MTRA Install*, is constrained by a four-hour thermal clock which starts at the beginning of the EVA; the second, *MISSE 8 Retrieve*, must be scheduled such that the first 20 minutes of the task occur during daylight (so that photographs can be taken). Another interesting aspect of this EVA is that since all the tasks are independent of each other, they all use a unique set of tools and equipment. Owing to limited carrying capacity, the crew members must translate to the Airlock to obtain the necessary tools and equipment at the beginning of each task and return there to drop them off at the end. As such, for most of the tasks, the beginning and ending location is the Airlock. This nuance of the tasks eliminates some flexibility the EPM could use to optimize their scheduling, but presents an interesting planning scenario. The full set of raw task data associated with this EVA, has been provided by the lead planners (J. Kagey & A. Battocletti, personal communication, August 23, 2012), and can be found in Appendix C. Figure 15 shows the current expert-developed timeline, labeled "heuristic" along with the EPM optimal solution. The EPM solve time for each of the scenarios in this section are highly satisfactory, ranging between two and four minutes. The subsections below detail some of the alternatives explored using EPM and the conclusions we have drawn from the results.

1. Task Selection

The first challenge of this planning scenario is to select the tasks that will be omitted from the plan since there is not enough time for all requested tasks. The expert planners have omitted two tasks, *JEM-EF Fwd Camera* and *MLM Ethernet Cable Install*, because they are the two lowest priority tasks. The EPM makes the same omissions due

in part to the lower priority value of the tasks, but also because of their relative length compared to similarly prioritized tasks. The *Node3 Fwd/Aft CBM Prep* and *FGB PDGF Troubleshooting* tasks, which have priority values just 10% greater than *JEM-EF Fwd Camera*, are scheduled instead - primarily because they have durations that are 25% and 50% shorter, respectively.

2. Priority Changes

To examine the effect of changing priorities, we simulate the common situation of the program customer mandating that a specific task be added to an EVA in development. Typically, a negotiation occurs in these situations, and the ability to generate alternative timelines is important to inform stakeholder decisions. As described in Chapter I, developing these alternatives is time consuming for the planners and there usually is not adequate time to explore all possible options.

Our simulation of this scenario involves one change to the previous EVA "A" model inputs: flagging *JEM-EF Fwd Camera* as mandatory. The bottom-most timeline in Figure 15 is the resulting optimal solution. An interesting effect of this change is that the EPM does not simply remove the next-lowest priority task from the plan. Instead it removes *Z1 Jumper Route/Install*, the fourth-highest priority task. In doing so, however, it replaces it with both the now-mandatory task and also the previously omitted *MLM Ethernet Cable Install*. If this outcome is also unsatisfactory to the program customer, other input parameters may be adjusted in turn, conveying the trade-offs and costs of new or updated requirements.

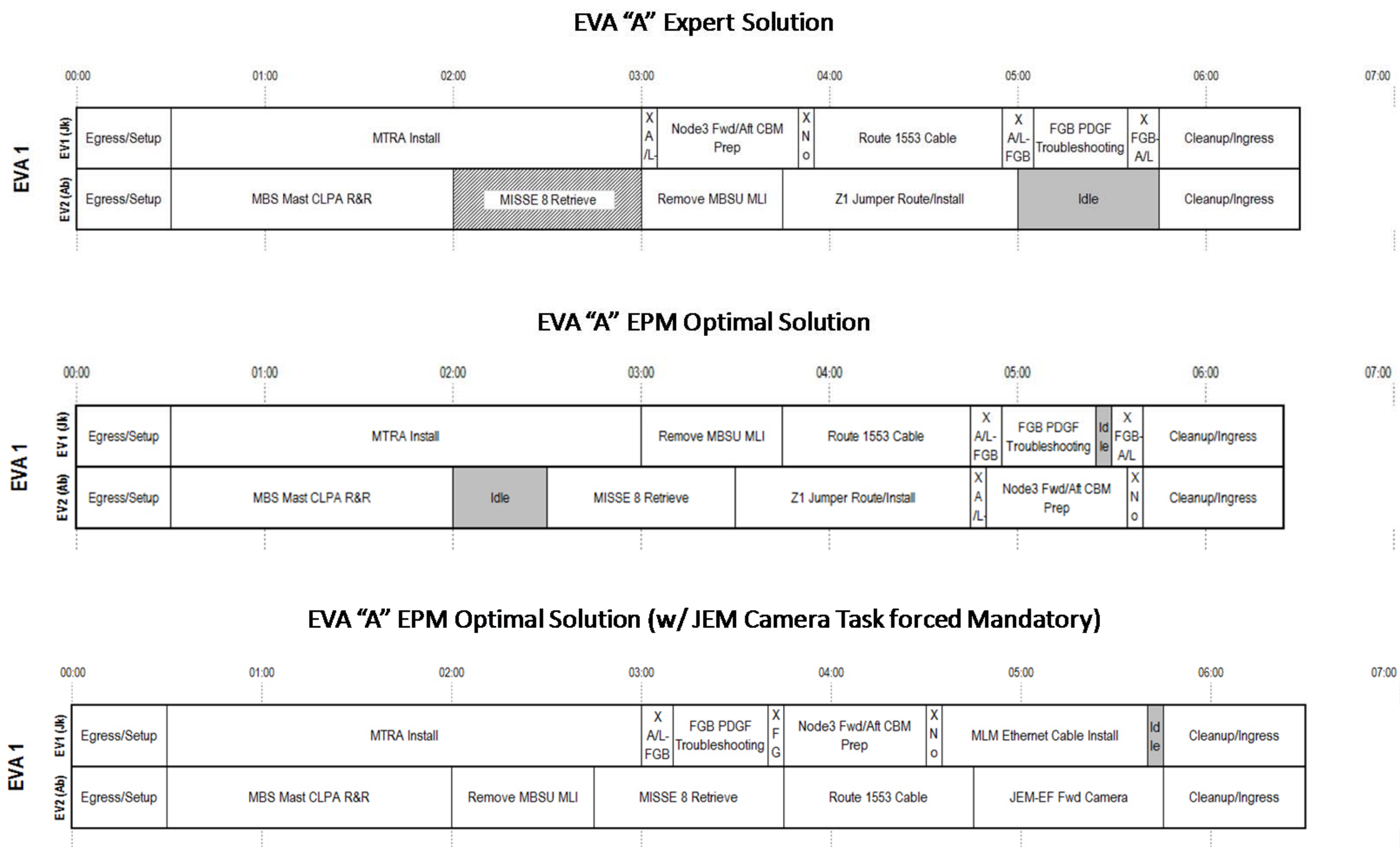
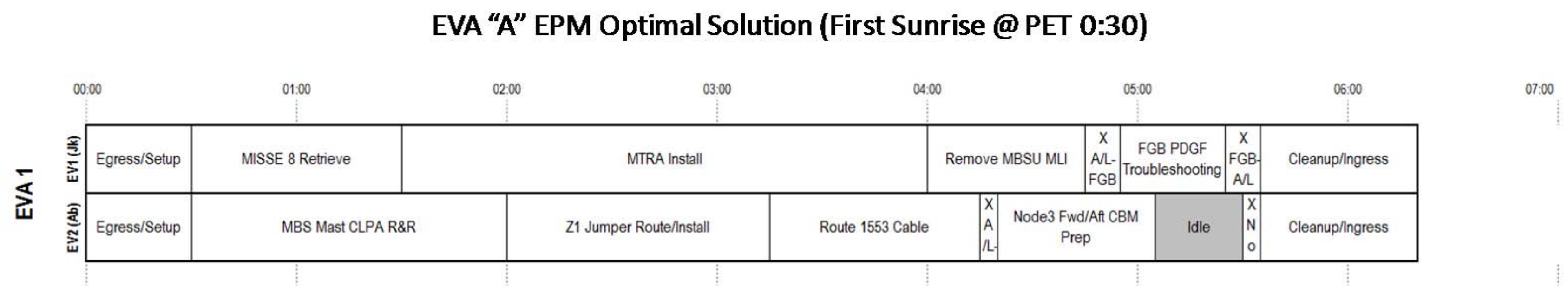


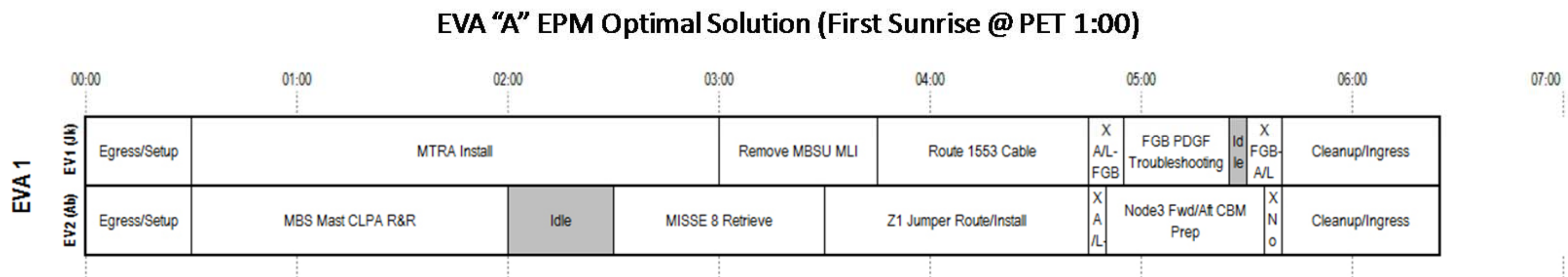
Figure 15. EVA "A" timelines (with first sunrise at 1:00 PET)

3. Day/Night Phasing

One immediate advantage of utilizing the EPM is clear when considering the EVA "A" case: the ability to plan for the daylight constraints on the *MISSE 8 Retrieve* task. Since the execution date of the EVA is unknown at this time, it is impossible for the planners to know what the actual day/night timing will be with respect to PET (referred to as "phasing"). The planners have no choice but to ignore this factor for the time being and create their EVA plan as if the constraint did not exist. This approach carries the risk that when the actual day/night phasing becomes known, it could result in substantial disruption to the timeline. Such a perturbation must then be addressed at a relatively late stage of the planning process. The EPM allows the planners to examine a range of different day/night phasing to assess the impact it has on the optimal plan far earlier in the process.

To investigate these effects, several day/night phasing cases have been tested. Figure 16 shows three timelines; all are optimal plans given their respective phasing, which is defined by the PET of the first sunrise during the EVA. Optimal timelines corresponding to first sunrises at PET of 30, 60, and 90 minutes are shown. A notable conclusion we can draw from these alternatives is that the heuristic solution, which schedules *MISSE 8 Retrieve* at 2:00 PET, is only feasible in one of these cases (sunrise at 0:30 PET) and even in that case it is not optimal. This tells us that it is highly likely the planners will have to adjust the timing of this task eventually. Knowing that, it is important to observe that although the *MISSE 8 Retrieve* task is the only one impacted by day/night phasing, the changes to the timeline extend well beyond just the timing of this one task. Without a capability to examine all the possible outcomes ahead of time, a human planner may be forced to wait for the phasing information to become available and then implement the suboptimal solution of simply sliding the task start time forward or back by enough minutes to make the lighting conditions acceptable. In taking this approach, they would be inherently diminishing the efficiency of the EVA.





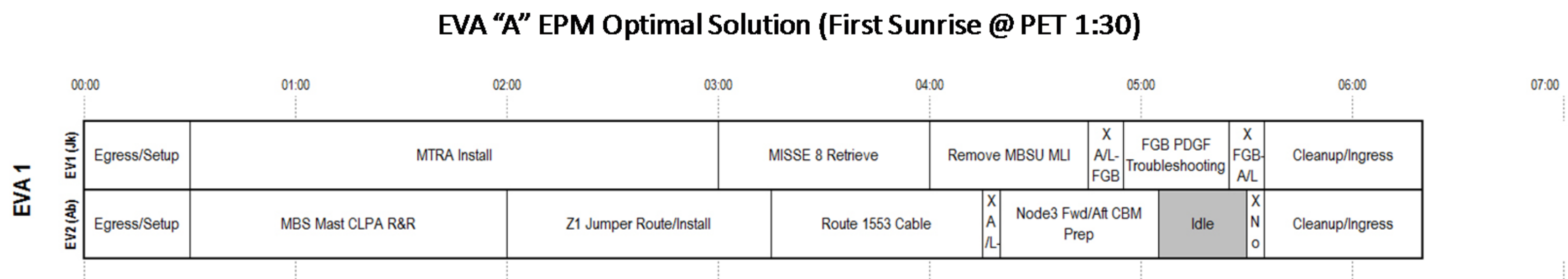


Figure 16. EVA "A" timelines with varying day/night phasing

D. EXPERT EVALUATION OF EPM

The EPM has been demonstrated for current and former EVA planning experts in order to solicit their opinions about its capabilities and usefulness. These demonstrations include the two EVA planning scenarios described in this chapter and static presentations of the EPM's features and results. Data have been gathered via expert survey questionnaires. The sample size is limited to four experts, in part by the small number of such experts available, and also due to ongoing EVA operations filling their schedules. As a result, this evaluation is not presented as a scientific study, but rather as a generalized indicator of the potential of the EPM tool and areas of improvement.

The EPM has been well received by all four EVA planning experts surveyed. All indicate they would be inclined to utilize such a tool if it were available. They rate the timelines produced by the model as credible. One evaluator points to preterition in defining input data as a cause of deficiencies noted in the resulting plan. When asked to evaluate the usefulness of the EPM, experts rate it highest (average rating of 4.33 on a five-point scale) in three categories: (1) plan development and trade-space evaluations, (2) preparing for stakeholder negotiations, and (3) increased ability to assess alternatives. One expert noted:

> I would use the tool primarily during discussions with the ISS Program and Flight Director Office [a key stakeholder within MOD]. In my experience, they like to see many options and sometimes think arranging [the plan] a little different would create more [free time in the plan]. This tool would have made those demonstrations much quicker and less work involved for the EVA team. It may also convince upper level management that if you really want all those tasks completed, you need to schedule another EVA.

Another expert acknowledges the potential of EPM to save time and expense in initial timeline development for specific types of EVAs, stating:

> For EVAs with one long task and highly constrained sequencing, the tool would not be as useful. But it would be useful in early EVA plan development when assessing how to schedule smaller tasks across a single or multiple EVA. In many cases the EVA planners scuba dive or perform a suited NBL run to evaluate proposed timelines. This can be an iterative

> process as we develop a timeline. Having a good starting point would help reduce the number of iterations and could help illustrate specific trades/options.

The quote above agrees well with our observations of the two distinct types of EVA planning scenarios described in this chapter. The LEE R&R EVA is a "highly constrained sequencing" scenario where the EPM output offers little more than matching the expert-developed timeline, while EVA "A" is a less constrained problem and demonstrates the power of the EPM to identify and assess alternatives.

The EPM is rated lower in its perceived ability to save time in plan development, largely due to the data entry requirements and unpolished user interface. The user interface and manual entry of task data is noted in multiple expert evaluations as a weakness, one stating: "I think the longest pole is getting all of the initial data into the system. If it is not too long then I think this could be real [*sic*] helpful." Another respondent points out:

> Inputting the tasks and restrictions could be more user friendly. Being able to save these tasks to a database so future runs could pick and choose already developed tasks along with new items would also be helpful.

Given the general reluctance to adopt new tools and embrace "automation" in processes that have historically been very hands-on and the fact that most of the deficiencies noted are related to the user interface and not the core capability of the EPM, the expert evaluations are a positive sign that EPM may become a helpful tool in the process of EVA planning.

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V. FUTURE WORK

The EPM has been developed to a proof of concept level as part of this research. The model has proven to be a usable tool that can help inform decision making during EVA planning even in its current form. There are many improvements that can, and should, be made to the model if its development is to continue with the goal of operational use.

A. ADDITIONAL FUNCTIONALITY

We use the term functionality to refer to the real-world planning considerations that are implemented by the model. Precedence relationships and asynchronous translation times are examples of two functions in the current EPM. There are many other functions that could be added to the model, some of which (e.g., task subdivision) are extraordinarily difficult problems. This section focuses on functionality that could be added in a follow-on revision rather than on the litany of capabilities that could be added in the more distant future.

1. Tool Constraints

Tools are an extremely important part of EVA planning and execution. The current EPM does not address tool requirements or constraints and adding this capability would be a major enhancement. This functionality could include a limit on how many tools can be carried at once, automatic addition of tool logistics tasks (for instance, translating to a tool box location to exchange tools), and ensuring that a unique tool is not needed by one crew member while the other crew member is using it elsewhere.

2. Task Synergy

Task synergy was mentioned in Chapter I as having a role in planning considerations. It was not implemented because in the current model architecture, all tasks considered are unique and individual. They can only be related to each other through precedence. In reality, tasks can be interlinked in different ways. For example, some tasks may have common steps which can yield substantial efficiency gains if the

tasks are performed adjacent to one another during the EVA. To envision this, consider three tasks whose first step is the removal of the same thermal cover. In the current model, each of the tasks would be entered with a duration that includes the removal and replacement of the thermal cover. The EPM would be aware of only one efficiency: that the tasks have the same location. However, in reality, if any one of the tasks is scheduled, the other two would be less time consuming when performed in immediate sequence with it. This type of relation is more difficult to implement than simple precedence because there is no need to stipulate the order in which they occur and the effect of them being scheduled "together" is a reduction in the duration of some of the tasks.

3. Task Exclusivity

Task exclusivity is another way in which tasks can be linked. This category involves groups of tasks that are mutually exclusive. For example, consider a case where three camera replacement tasks are possible. In the current model, they become independent tasks which have no relation to each other. However, if there are only two spare cameras available, then only two of the three tasks may be scheduled. The ability to eliminate a set of tasks from consideration if another task has been completed would be fairly simple to add in a future version of the EPM. Conversely, there may be some tasks that should always be performed together (although not necessarily in a specific order or concurrently). To add that type of functionality, a set of tasks would become mandatory if and only if another task or tasks have been scheduled.

4. Robotics Integration

Many, if not most, EVAs employ the ISS robotic arm. Robotics may be used to assist the crew in translating across long distances, help them reach difficult worksites, or allow the positing of large or massive objects. Since robotic arm integration is such an important part of EVA, its omission from the first version of the EPM leaves the potential for significant improvement. In most of the cases examined for this research, we have found that robotic arm integration can be mimicked by manipulating translation times for locations known to be associated with robotics-assisted tasks. This is a makeshift fix that is inadequate for longer-term use and/or more realistic employment of the EPM.

B. MODEL PERFORMANCE

We have observed during black-box testing and in proof-of-concept runs of the EPM that its performance in terms of solution time is inadequate. EPM solve times are highly variable and increased dramatically with more complicated problems. For complex problems, solve times in the 24-hour range would not be unexpected. While this is not necessarily a problem for the generation of preliminary plans in the early phases of development, it could rule out use of the tool closer to, or in, real-time. Poor performance also works against the notion that an expert planner could use the model to generate a candidate timeline, evaluate it, change some parameters to adjust it, then re-run the model (and repeat). For that type of use scenario to be practicable, solve times would have to be in four-hour or less range (to facilitate multiple runs in a single work day).

There are many options to improve performance of the model, some of which have been explored on a limited basis during black-box testing. A more focused effort on altering CLPEX settings to tailor performance to our specific model could yield better results. Exploring the use of other solvers should also be undertaken. Finally, the model could be revised to reduce complexity and/or strengthen the formulation.

C. EASE OF USE

To facilitate expert user acceptance and more widespread testing of future versions of the EPM, ease of use could be improved. In the current version, all input data are entered through Microsoft Excel templates via 10 independent files that must be populated with information. This should be reduced to a more economical set of input files or replaced by a user friendly interface for data entry, possibly supported by a database of existing tasks (and other problem data) as suggested by one of the surveyed planners. The addition of embedded input error checks and validations (for example, ensuring that a task's duration does not exceed its bingo time), would be a beneficial refinement.

The output of the model is another area where usability can be enhanced. The raw output of the current EPM is comprised of one formatted text file showing the PET and tasks for each crew member and one Excel file that shows the tasks along with idle time

and translations. The former also provides a list of which input tasks have been omitted from the EVA. The Excel output file is used to more readily interface with an Excel Visual Basic macro that produces the graphical overview timelines seen in the figures of Chapters III and IV. These graphical views are commonly used by the planning experts and stakeholders. This process requires several intermediate steps, which could be streamlined to improve usability.

D. INTEGRATION WITH OTHER AUTOMATED PLANNING TOOLS

The possible integration of EPM with the task database, hierarchical task net information, and resource handling algorithms developed by TRACLabs (described in Chapter II) is an intriguing possibility. That work potentially holds the key to reducing the amount of manual data entry required for the EPM. It could also lead to enhancing the EPM's capabilities in areas highlighted above (e.g., tool constraint management) and in new areas such as detailed consideration of EMU consumables. Finally, it could enable the EPM to tackle the problem of task subdivision.

VI. CONCLUSION

EVA planning is a highly complex process requiring a high level of expertise. We have developed the EPM, a MIP that optimizes the EVA planning sub-problems of task selection, crew assignment, and task sequencing. The EPM proves the concept that formal combinatorial optimization can be used to successfully improve the efficiency of EVA timeline development. The EPM has been tested extensively both to verify its functionality and its usefulness in real-world EVA planning situations. It has been evaluated by EVA planning experts who cited time savings in plan development and especially in assessment of alternatives as major reasons they would want to use the tool.

We find that the EPM, while necessarily limited in its initial functionality, is able to provide complete and credible overview level timelines for two actual EVAs using only raw source data. We also find that it is capable of handling alternative planning scenarios commonly found in practice, including (1) the addition of extra tasks to a developed EVA plan, (2) a thorough analysis of orbital day/night phasing impacts upon EVA plans with tasks sensitive to such phasing, and (3) the changing of customer priorities during the planning process. Furthermore, the EPM has demonstrated enhanced trade-space evaluation by its ability to examine all feasible permutations of task selection, sequencing, and assignment and its creation of EVA plans as holistic entities rather than a series of sequential decisions as a human planner might.

The EPM can be improved in multiple ways. Although no test case takes more than 24 hours to reach an optimal solution, the model's solve-time performance is found to be highly variable and unpredictable. For example, some test cases take more than ten hours to solve, while others require less than five minutes. We have identified several other improvement areas for the EPM, including added functionality and friendlier user interface.

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APPENDIX A: LEE R&R EVA RAW DATA

This appendix provides data tables containing the raw input data used as EPM input for the LEE R&R EVA planning. These data have been gathered via personal communication with the lead EVA planner, F. Sabur (June 27, 2012).

	Priority	DurEV1	DurEV2	Mandatory	Tandem	Airlock	Toxic	HasWindow	HasBingo	BingoTime
PVGF_Release_from_EP	100	5	6	0	0	0	0	0	0	0
P1_Worksite_Setup	100	30	33	0	0	0	0	0	0	0
Remove_CLA	100	10	11	0	0	0	0	0	0	0
Translate_Failed_LEE_to_ELC1	100	30	30	0	1	0	0	0	0	0
Spare_LEE_Prep	100	45	50	0	0	0	0	0	0	0
Stow_Failed_LEE_on_Temp_Stow_Ring	100	25	25	0	1	0	0	0	0	0
Retrieve_Spare_Lee	100	40	40	0	1	0	0	0	0	0
Translate_Spare_LEE_to_P1_Worksite	100	30	30	0	1	0	0	0	0	0
Install_CLA	100	10	11	0	0	0	0	0	0	0
Install_LEE	100	30	30	0	1	0	0	0	1	305
LEE_FSE_Cleanup	100	9	10	0	0	0	0	0	0	0
Remove_Failed_LEE	100	30	30	0	1	0	0	0	0	0
Cleanup_Ingress	100	30	30	1	1	1	0	0	0	0
Egress_Setup	100	15	15	1	1	0	0	1	0	0

Table 11. Task Data

Task	Initial Location	Final Location
PVGF_Release_from_EP	HTV	HTV
P1_Worksite_Setup	Columbus_WIF3	P1_Worksite
Remove_CLA	P1_Worksite	P1_Worksite
Translate_Failed_LEE_to_ELC1	P1_Worksite	ELC1
Spare_LEE_Prep	ELC1	ELC1
Stow_Failed_LEE_on_Temp_Stow_Ring	ELC1	ELC1
Retrieve_Spare_Lee	ELC1	ELC1
Translate_Spare_LEE_to_P1_Worksite	ELC1	P1_Worksite
Install_CLA	P1_Worksite	P1_Worksite
Install_LEE	P1_Worksite	P1_Worksite
LEE_FSE_Cleanup	ELC1	ELC1
Remove_LEE	P1_Worksite	P1_Worksite
Cleanup_Ingress	Airlock	Airlock
Egress_Setup	Airlock	Airlock

Table 12. Task Locations

Predecessor	Successor
P1_Worksite_Setup	Remove_CLA
Remove_Failed_LEE	Translate_Failed_LEE_to_ELC1
Remove_CLA	Translate_Failed_LEE_to_ELC1
Translate_Failed_LEE_to_ELC1	Stow_Failed_LEE_on_Temp_Stow_Ring
Spare_LEE_Prep	Retrieve_Spare_Lee
Translate_Failed_LEE_to_ELC1	Retrieve_Spare_Lee
Retrieve_Spare_Lee	Translate_Spare_LEE_to_P1_Worksite
Remove_CLA	Install_CLA
Remove_Failed_LEE	Install_CLA
Translate_Spare_LEE_to_P1_Worksite	Install_CLA
Install_CLA	Install_LEE
Translate_Spare_LEE_to_P1_Worksite	Install_LEE
Retrieve_Spare_Lee	LEE_FSE_Cleanup
Stow_Failed_LEE_on_Temp_Stow_Ring	LEE_FSE_Cleanup
Translate_Spare_LEE_to_P1_Worksite	LEE_FSE_Cleanup
Remove_CLA	Remove_Failed_LEE
P1_Worksite_Setup	Remove_Failed_LEE
PVGF_Release_from_EP	Remove_Failed_LEE
Stow_Failed_LEE_on_Temp_Stow_Ring	Retrieve_Spare_Lee

Table 13. Precedence Relationships

To / From	Airlock	HTV	ELC1	P1_Wrkst	Col_WIF3
Airlock	0	10	15	13	8
HTV	10	0	20	13	2
ELC1	15	20	0	13	20
P1_Wrkst	13	13	13	0	13
Col_WIF3	8	2	20	13	0

Table 14. Translation Times

		tmin	tmax
w1	Egress_Setup	0	30

Table 15. Task Time Windows

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APPENDIX B: LEE R&R EVA RAW DATA (ALTERNATE)

This appendix provides data tables containing the raw input data used as EPM input for the alternate LEE R&R EVA planning. These data have been gathered via personal communication with the lead EVA planner, F. Sabur (August 13, 2012). Only tables with changes from the baseline LEE R&R case are shown.

	Priority	DurEV1	DurEV2	Mandatory	Tandem	Airlock	Toxic	HasWindow	HasBingo	BingoTime
PVGF_Release_from_EP	100	5	6	0	0	0	0	0	0	0
P1_Worksite_Setup	100	30	33	0	0	0	0	0	0	0
Remove_CLA	100	10	11	0	0	0	0	0	0	0
Translate_Failed_LEE_to_ELC1	100	30	30	0	1	0	0	0	0	0
Spare_LEE_Prep	100	45	50	0	0	0	0	0	0	0
Stow_Failed_LEE_on_Temp_Stow_Ring	100	25	25	0	1	0	0	0	0	0
Retrieve_Spare_Lee	100	40	40	0	1	0	0	0	0	0
Translate_Spare_LEE_to_P1_Worksite	100	30	30	0	1	0	0	0	0	0
Install_CLA	100	10	11	0	0	0	0	0	0	0
Install_LEE	100	30	30	1	1	0	0	0	1	305
LEE_FSE_Cleanup	100	9	10	0	0	0	0	0	0	0
Remove_Failed_LEE	100	30	30	0	1	0	0	0	0	0
Cleanup_Ingress	100	30	30	1	1	1	0	0	0	0
Egress_Setup	100	15	15	1	1	0	0	1	0	0
PMA2_Cover_Install	60	20	20	0	1	0	0	0	0	0
SSRMS_Boom_Camera_Replace	65	35	35	0	0	0	0	0	0	0
Retrieve_Mast_Camera	50	15	15	0	0	0	0	0	0	0

Table 16. Task Data

Task	Initial Location	Final Location
PVGF_Release_from_EP	HTV	HTV
P1_Worksite_Setup	Columbus_WIF3	P1_Worksite
Remove_CLA	P1_Worksite	P1_Worksite
Translate_Failed_LEE_to_ELC1	P1_Worksite	ELC1
Spare_LEE_Prep	ELC1	ELC1
Stow_Failed_LEE_on_Temp_Stow_Ring	ELC1	ELC1
Retrieve_Spare_Lee	ELC1	ELC1
Translate_Spare_LEE_to_P1_Worksite	ELC1	P1_Worksite
Install_CLA	P1_Worksite	P1_Worksite
Install_LEE	P1_Worksite	P1_Worksite
LEE_FSE_Cleanup	ELC1	ELC1
Remove_Failed_LEE	P1_Worksite	P1_Worksite
Cleanup_Ingress	Airlock	Airlock
Egress_Setup	Airlock	Airlock
PMA2_Cover_Install	PMA2	PMA2
SSRMS_Boom_Camera_Replace	S0_F2_WIF22	S0_F2_WIF22
Retrieve_Mast_Camera	MT_WS4	MT_WS4

Table 17. Task Locations

Predecessor	Successor
P1_Worksite_Setup	Remove_CLA
Remove_Failed_LEE	Translate_Failed_LEE_to_ELC1
Remove_CLA	Translate_Failed_LEE_to_ELC1
Translate_Failed_LEE_to_ELC1	Stow_Failed_LEE_on_Temp_Stow_Ring
Spare_LEE_Prep	Retrieve_Spare_Lee
Translate_Failed_LEE_to_ELC1	Retrieve_Spare_Lee
Retrieve_Spare_Lee	Translate_Spare_LEE_to_P1_Worksite
Remove_CLA	Install_CLA
Remove_Failed_LEE	Install_CLA
Translate_Spare_LEE_to_P1_Worksite	Install_CLA
Install_CLA	Install_LEE
Translate_Spare_LEE_to_P1_Worksite	Install_LEE
Retrieve_Spare_Lee	LEE_FSE_Cleanup
Stow_Failed_LEE_on_Temp_Stow_Ring	LEE_FSE_Cleanup
Translate_Spare_LEE_to_P1_Worksite	LEE_FSE_Cleanup
Remove_CLA	Remove_Failed_LEE
P1_Worksite_Setup	Remove_Failed_LEE
PVGF_Release_from_EP	Remove_Failed_LEE
Stow_Failed_LEE_on_Temp_Stow_Ring	Retrieve_Spare_Lee
Install_LEE	SSRMS_Boom_Camera_Replace

Table 18. Precedence Relationships

	Airlock	HTV	ELC1	P1_Wrkst	Col_WIF3	PMA2	MT_WS4	S0_WIF22
Airlock	0	13	10	8	10	13	32	34
HTV	13	0	20	10	2	2	31	33
ELC1	10	20	0	10	20	22	37	41
P1_Wrkst	8	10	10	0	10	13	17	21
Col_WIF3	10	2	20	10	0	2	32	34
PMA2	13	2	22	13	2	0	34	36
MT_WS4	32	31	37	27	32	34	0	24
S0_WIF22	34	33	41	31	34	36	24	0

Table 19. Translation Times

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APPENDIX C: EVA "A" RAW DATA

This appendix provides data tables containing the raw input data used as EPM input for the EVA "A" planning. These data have been gathered via personal communication with the lead EVA planners, J. Kagey and A. Battocletti (August 23, 2012).

	Priority	DurEV1	DurEV2	Mandatory	Tandem	Airlock	Toxic	HasWindow	HasBingo	BingoTime
Egress_Setup	1	30	30	1	1	0	0	1	0	0
MBS_Mast_CLPA_RR	100	90	90	0	0	0	0	0	0	0
MTRA_Install	90	150	150	0	0	0	0	1	0	0
MISSE_8_Retrieve	95	60	60	0	0	0	0	1	0	0
Node3_Fwd_Aft_CBM_Prep	50	45	45	0	0	0	0	0	0	0
Route_1553_Cable	55	60	60	0	0	0	0	0	0	0
Remove_MBSU_MLI	60	45	45	0	0	0	0	0	0	0
Cleanup_Ingress	0	45	45	1	1	1	0	0	0	0
Z1_Jumper_Route_Install	85	75	75	0	0	0	0	0	0	0
FGB_PDGF_Troubleshooting	50	30	30	0	0	0	0	0	0	0
JEM_EF_Fwd_Camera	45	60	60	0	0	0	0	0	0	0
MLM_Ethernet_Cable_Install	40	65	65	0	0	0	0	0	0	0

Table 20. Task Data

Task	Initial Location	Final Location
Egress_Setup	Airlock	Airlock
MBS_Mast_CLPA_RR	Airlock	Airlock
MTRA_Install	Airlock	Airlock
MISSE_8_Retrieve	Airlock	Airlock
Node3_Fwd_Aft_CBM_Prep	Node3	Node3
Route_1553_Cable	Airlock	Airlock
Remove_MBSU_MLI	Airlock	Airlock
Cleanup_Ingress	Airlock	Airlock
Z1_Jumper_Route_Install	Airlock	Airlock
FGB_PDGF_Troubleshooting	FGB	FGB
JEM_EF_Fwd_Camera	Airlock	Airlock
MLM_Ethernet_Cable_Install	Airlock	Airlock

Table 21. Task Locations

Predecessor	Successor
Egress_Setup	Cleanup_Ingress

Table 22. Precedence Relationships

	Airlock	ELC2	MT	Node3	Z1	JEM	FGB	Node1
Airlock	0	12	8	5	8	15	10	5
ELC2	12	0	8	17	16	20	22	17
MT	8	8	0	13	16	10	18	13
Node3	5	17	1	0	5	15	5	2
Z1	8	16	16	5	0	20	8	5
JEM	15	20	10	15	20	0	20	20
FGB	10	22	18	5	8	20	0	5
Node1	5	17	13	2	5	20	5	0

Table 23. Translation Times

		1st Sunrise @ 0:30 PET		1st Sunrise @ 1:00 PET		1st Sunrise @ 1:30 PET	
		tmin	tmax	tmin	tmax	tmin	tmax
w1	Egress_Setup	0	30	0	30	0	30
w1	MTRA_Install	0	240	0	240	0	240
w1	MISSE_8_Retrieve	30	115	60	145	1	86
w2	MISSE_8_Retrieve	120	205	150	235	90	175
w3	MISSE_8_Retrieve	210	295	240	325	180	265
w4	MISSE_8_Retrieve	300	385	330	390	270	355

Table 24. Task Time Windows (for three day/night phasing cases)

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